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TRANSFERRING TECHNICAL KNOWLEDGE AND INNOVATING IN EUROPE, c.1200-c.1800

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Les arts ne passeront jamais par écrit d'une nation chès l'autre; les yeux seuls et l'habitude peuvent former les hommes à ces travaux. (Trudaine de Montigny 1762: 64)

1. INTRODUCTION

The role of technology in the transition from premodern, 'Malthusian' to modern economies in late eighteenth- and nineteenth-century Europe is among the major questions in economic history, but it is still poorly understood. In particular, the view that technological change before c.1800 was close to zero due to poorly specified property rights to knowledge and pervasive rent seeking by guilds is hard to square with the fact that the surge of technological innovation in the eighteenth century occurred within institutional frameworks not too dissimilar to those of 1300 (North 1981; Mokyr 2002).

A plausible explanation of premodern European technological development and industrialisation must account for three established facts. First, in the early thirteenth century Europe was still a technological backwater by comparison with the great Asian civilisations. Only a process of small-scale incremental innovation in metallurgy and instrument making, mining, building and shipbuilding, chemical process and cloth production, can explain the technological and industrial success of steam power—the most salient European contribution to premodern technical knowledge—six centuries later. The most striking feature by comparison with other coeval societies, however, is not so much that technological progress in premodern Europe occurred at a faster rate than elsewhere, but that progress was persistent and uninterrupted. By contrast, technological development in the great Asian civilizations of India and China experienced comparatively short periods of efflorescence, lasting a few centuries at a time, which were regularly followed by long phases of near-stagnation.

Second, the geographical location of technological leadership in premodern Europe moved over time. Between the eleventh and the nineteenth centuires, Europe's technological frontier shifted increasingly north-west: from the east-central Mediterranean to northern Italy during the thirteenth and fourteenth centuries, to southern Germany and Bohemia in the late fifteenth, to the southern Low Countries in the sixteenth, to the Dutch Republic and finally to Britain during the seventeenth and eighteenth (Davids 1995). Each new regional leader added the innovations of its predecessors to its local technical stock and recombined them for further technological advances. Although leadership was temporary, falling prey over time to technological sclerosis, declining marginal returns, and rent seeking by producers and elites, loss of leadership did not lead to a technological dead end. The existence of an increasingly integrated Europen market for skilled labor with a great deal of 'ecological' variation in demand, and of many polities whose rulers' peaceful and military competition created spatial and temporal variation in demand for skills, generated the market and institutional conditions for new technological growth poles to take over.

Last, the technical knowledge of premodern craftsmen and engineers was largely experience-based (Reber 1993). Thus, practically all premodern technical knowledge—which I define simply as knowledge of how to make things, and get them right—had to be transferred in the flesh. The shifts in regional technical leadership I just described could therefore only occur if technicians could take their knowledge elsewhere. This was arguably more easily done in Europe than in other parts of Eurasia, because European technicians were not members of ascriptive (kin-, religion- or locality-based) communities, and because they benefited from competitive bidding for technical expertise across a fragmented political and economic system.

The implications for premodern economic history of the basic cognitive limitations to how technical knowledge can be expressed, processed and transmitted have yet to be examined in any detail. This paper asks how premodern European societies were able to generate incremental technical innovation under three headings: How was *established and new knowledge* transmitted? How was premodern technical knowledge *stored* to avoid loss? How were tacit, visual, verbal, and written means of transmission used *heuristically*? In answering these questions, I aim to sketch a model of endogenous technological progress that incorporates and explains the three stylised processes outlined above. I focus mainly on the period before 1700, in order to emphasize the similarities with better-known eighteenth-century conditions. Section 2 discusses the nature of experiential knowledge and its intergenerational transfer. Section 3 addresses knowledge transfer between peers, including technical codification and heuristics. Section 4 discusses technological transfer across space. Section 5 concludes.

2. ACQUIRING EXPERIENTIAL KNOWLEDGE

2.1 Apprenticeship

In discussing the experiential knowledge of premodern technicians (craftsmen and engineers), I take as premise the fact that intelligent behaviors, long associated with the overt and conscious domain of cognitive functioning, are better understood as the result of both implicit and explicit capacities. Thus, experiential knowledge includes implicit or tacit knowledge; non-propositional and non-linear knowledge, including imagery, which has both implicit and explicit components; and explicit, propositional knowledge, which is linear and verbal or mathematical. Implicit knowledge equates to knowledge that is acquired largely independently of conscious attempts to learn, and largely in the absence of explicit knowledge about what was acquired. Implicit knowledge relies on rule finding and abstraction, and is the basis for the acquisition of skills. Thus, the distinction between implicit and explicit knowledge is hazy, and they form part of a continuum; but the implicit component is consistently greater than the explicit.

Also on this definition, the boundaries between experiential knowledge in technical activities and in the sciences are far fuzzier than assumed by standard claims that technical practice and experimentation is 'non-scientific' because it lacks an underlying conceptual or propositional framework (e.g. Raven 2005). There is no scope here to enter the debate on the relative significance of scientific and non-scientific thinking and practice for the Industrial Revolution, recently rekindled by Joel Mokyr, but it may be useful to set out this paper's underlying assumptions on the matter. Following a now established tradition of studies of scientific practices that emphasises their craft-like characteristics (Collins 1985, 2001, 2004; Winter ***; Schaffer ***; Shapin 1988; Klein 2005) I assume that the major distinction between scientific and technical practice for the purposes of economic history is not cognitive (e.g. one between the craftsman's 'common-sense' and the scientist's 'counter-intuition' (Floris Cohen 2004: 120)), but resides in differences in the aims and forms of codification (which in this context includes varieties of modelling). In this view, scientists' main epistemological objective is to identify and codify regularities, for codification is essential both to communicate, convince, and establish credentials, and to establish a shared base for further advance. Technicians, by contrast, identify and codify regularities only as a means to an end, the end being to make things work reliably and well (e.g. efficiently in a broad sense of the term). They do not avoid codification in principle, but they generate it less systematically than scientists and they do so largely in interaction with, rather than independently of, the production process itself. The main practical consequence of this epistemological distinction is that scientists (and scientific practice) are primed to identify a greater number of regularities in their knowledge base. Many of these regularities are technologically useless—they are part of what is popularly known as 'pure science'—but some may turn out to have technological (material) applications.

At the same time, both scientists and technicians rely on experiential knowledge that is hard or impossible to codify. Experiential knowledge is a good, and its exchange and diffusion demand that those who have it take deliberate action to share it through face-to-face communication. These operations are costly to implement, and have relied historically on different institutional solutions. Analytically, it is useful to break down the question how technical knowledge was transferred into the issues of inter-generational transmission and transmission between skilled peers.

The first stage in acquiring technical knowledge was through a long-term relationship of pupilage based on formal or informal sanction, in other words through apprenticeship. Apprenticeship broadly defined is the chief means for acquiring technical knowledge outside the family devised by human societies. By enabling apprentices to finance skills acquisition with a below market wage during training, apprenticeship solves the problem that trainees lack the capital to pay for training in advance.

In medieval and early modern Europe, parents or guardians (including people acting for religious foundling institutions) would usually present a child for apprenticeship between the ages of 13 and 15; but not all apprentices were adolescents, and guild statutes never specified the maximum

age at which the indenture could begin. Most statutes set the minimum term of service, proportionate to the craft's skill requirements and to its expected returns. Thus the average length, which appears to have increased slowly over time, was variable; the English Statute of Artificers (1563, repealed 1814), which prescribed a national norm of 7 years terminating at age 24 or older, was unique. Even in England, however, the actual length of service was negotiated individually on the basis of the apprentice's age and prior experience, of the premium (if any) the parents' could advance, and of the master's reputation. Most statutes required longer terms for outsiders than for sons of members, who would have experienced some basic induction to the craft in their father's shop. Apprenticeship years could also be bought out at a later date, or condoned if the trainee could demonstrate sufficient skills. Duration was further influenced by the fact that before the dissolution of craft guilds apprenticeship was not just a traineeship for a skilled occupation, but also a means for socializing children and adolescents into adulthood and world of work, so that the term was longer the younger the age at entry.

The duration of training does not capture the intensity of resources expended during it. Apprenticeship training was costly, because skills and expertise take time and effort to acquire. Expertise depends on two main processes: heuristic search of problem spaces, and the recognition of cues that access relevant knowledge and suggest heuristics for the next step. Experts store thousands of 'chunks' of information in memory, accessible when they recognize relevant cues. Experts use these recognition processes to achieve unusual feats of memory, reorganize knowledge into complex hierarchical systems, and develop complex networks of causally related information. The knowledge of less skilled individuals, in contrast, is encoded using everyday concepts that make the retrieval of even their limited knowledge difficult and unreliable. It consequently takes about 10 years of focused training to acquire top-level expertise in activities as diverse as chess, dog training, wine tasting, playing and composing music, sports, and, possibly, language acquisition (Ericsson, Krampe and Tesch-Römer 1993). There is no reason to believe that the length of training would be any different in areas of more practical expertise—a fact plausibly reflected in the lengthy technical apprenticeships of premodern Europe.

Secondly, apprenticeship was costly because most craft knowledge was experiential.[1] Consequently, craft statutes and labour laws never specified the content of the training regime. Crafts were not learned prescriptively, because training was in the master craftsman's head and hands; instead, craftsmen and women tested the quality of training by examining its outcome. The acquisition

[1] The salience of implicit knowledge and experience provided an inbuilt advantage to employing family members, who had been socialised early into the craft and generated higher levels of trust, particularly in the most technically advanced industries like mining and metal-working, ship- and high quality edifice building, and clock and instrument making. For similar reasons, highly specialised craft knowledge and techniques were often transmitted through craft lineages; see e.g. Brown, 1979.

of technical expertise was sanctioned through a mastership. Starting in the late thirteenth century and with increasing frequency from the late fourteenth, candidates to mastership in the most highly skilled crafts had to prove their skills through examination or by making a masterpiece (Cahn 1979). The masterpiece combined a physical embodiment of collective knowledge and individual creativity and virtuosity ('genius'). It was a demonstration of skill and of self-confidence that the proposed product could be constructed and would work; and it established the expert as someone who had assimilated tradition so well that he could adapt, modify and transcend it. Expertise also made it easier to formulate non-verbal practices and heuristics explicitly, as Salviati, on the first day of Galileo's *Discourses*, famously remarks: 'The constant activity which you Venetians display in your famous arsenal suggests to the studious mind a large field for investigation … for … all types of instruments and machines are constantly being constructed by many artisans, among whom there must be some who, partly by inherited experience and partly by their own observations, have become highly expert and clever in explanation' (Galilei 1638: 1-2). Expertise, in other words, was also a precondition for the ability to teach, and teaching apprentices helped solve the conundrum of making tacit technical knowledge, public.

Standard economic theory explains why apprenticeship was needed. Since future human capital cannot act as collateral, resource poor but potentially able workers may be incapable of bearing the costs of their investment in skills, leading to a socially suboptimal supply of skilled workers. Premodern apprenticeship allowed trainees to exchange subsidized training for below-market wages after training was concluded. However, masters would have still supplied suboptimal amounts of training if the trainee could quit before contract expiry because the training masters could not capture the full return to their investment. Trainees with transferable skills (which are neither entirely general nor wholly specific to one firm) would be poached by masters that did not have to recover the training costs and that could pay them less than their marginal product but more than the wage paid by the original master. For apprenticeship to be viable, poaching had to be constrained through legally enforceable indentures, which allowed the masters that provided the training to appropriate the full benefits in the immediate post-training period.

In premodern Europe, this enforcement was provided largely, though not solely, by craft guilds; for in the absence of compulsory schooling, supra-local legislation, and efficient bureaucracies, formal or informal craft associations were best suited to enforce apprenticeship contracts and rules outside the family.[2] Craft guilds overcame externalities in human capital formation by supervising job

[2] Large numbers of children were also never apprenticed because they were trained within their parents' homes, or because some crafts (particularly those involving trade) did not require formal training; this fact accounts for the low number of apprentices with practicing masters relative to the number of masters and journeymen that were needed to reproduce trades over time, and for the low number of working girls recorded. Conversely, apprenticeship could exist outside guild structures, although it faced the problem of enforcement outside a

performance, work conditions, and quality of instruction; enforcing contracts through compulsory membership, statutory penalties, and blackballing; and protecting apprentices against poor training in craft specific skills within oligopsonistic labour markets. Live-in apprentices had the right to be lodged, fed, housed, clothed, and heated on a par with members of their master's family, but they were equally subjected to his disciplinary rule as a surrogate father. Even those apprentices who lived at their parents' home (which they did in increasing numbers from the late seventeenth century) were expected to pay unquestioning obedience to the master's orders and respect the craft's rules. The apprentices' minority status explains the universal ban on marriage, and why breaches of the rule were treated severely, while the contract's educational features explain why younger trainees were set longer terms. The master controlled the apprentice's work-time, and could offer the apprentice's labour to another guildsman; the apprentice had to work to the master's benefit and profit, and the guild enforced the master's right to keep the apprentice on after his training had been completed so as to repay the master's training costs.

Guilds, however, were more effective in banning poaching by their members than in stopping apprentices from quitting before their term ended. Masters tried to reduce this by demanding entry fees (de facto bonds posted to ensure the apprentice's commitment for the full term), by setting apprentices' wages on a rising scale for the contract's duration, and by promising a pay-off upon completion, but there was little they could do to fully stem the hemorrhage. The rate of attrition in early modern England has been estimated at 30 to 50 per cent in sixteenth and seventeenth-century London, Bristol and Norwich. Although a significant proportion of apprentices who quit early were simply unable to cope, were mistreated, or moved to another occupation, many left in search of work in the rural and small town provinces where skill requirements were lower: crafts in pre-modern towns acted as training centers for their regional or even, in the case of London and other capital cities, national hinterlands, which they provided with a constant flow of skilled and semi-skilled labour. Such high rates of defection would suggest that masters were unable to fully recover their training costs, and that the reason they were nonetheless willing to train is that they had ex post monoposony power arising from their superior information about their employees' abilities (Acemoglu and Pischke 2001). Rising rates of defection might also explain attempts to extend the minimum length of the apprenticeship contract, although as explained above, statutory lengths were easily evaded.

Many of the departing apprentices had originally immigrated to the town from the urban hinterland. This gave rise to problems of adverse selection and asymmetric information, which guilds and governments addressed by stipulating entrance requirements that signaled the laborer's quality or provided surety against misbehavior, such as place of residence, family income, or the father's

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formal institutional framework. For these reasons and because of the nature of the skills involved, apprenticeship was mainly an urban, craft-based phenomenon, although in seventeenth- and eighteenth-century England it was also undertaken by the children of the rural poor under the remit of the national Poor Laws.

occupation; the Statute of Artificers specified all three. In some highly specialized and cyclical industries, like mining and iron-making, ship building and high-quality masonry, skills training was often kept within closely knit kin networks, possibly because the higher risks of those industries restricted the supply of apprentices.

Evidence that apprenticeship achieved its stated purpose and was not simply a means to exclude workers from the market and a source of rents for craftsmen is twofold. First, practically all crafts's jurisdiction extended only as far as their town or city walls, so there was ample scope for more efficient means of training to develop in the surrounding countryside, or in the many towns and cities where the rule of craft guilds did not apply. Although as mentioned, craft guilds were not the only way of enforcing apprenticeship contracts, before the nineteenth century the crafts' primacy in training highly skilled labour was largely unchallenged. Second, the sharp rise during the fourteenth and fifteenth century in the number of guilds (**Figure 1**), together with a growing emphasis on formal apprenticeship, anti-poaching rules, and final examinations, appears to have produced a substantial increase in the supply of skilled labour after 1350. Evidence of this comes from the sharp and permanent fall in the wage ratio between skilled and unskilled labour in the building industry (the only one with adequate data) after the Black Death wage, from c. 2.2-2.3 : 1 (1300-25) to c. 1.5-1.7 : 1 (1500-25) (van Zanden 2004) (**Figure 2**).

In sum, craft guilds restricted the mobility of workers so that masters could earn rents on trained workers. This may have restricted the efficient allocation of workers to firms, but it did supply critical institutional support for the provision and transmission of skills (Acemoglu and Pischke 2001). In this sense, crafts helped the European economy achieve a higher-level equilibrium, and also explains the extraordinary longevity of European craft guilds from the late eleventh century to the early nineteenth (Epstein 1998).

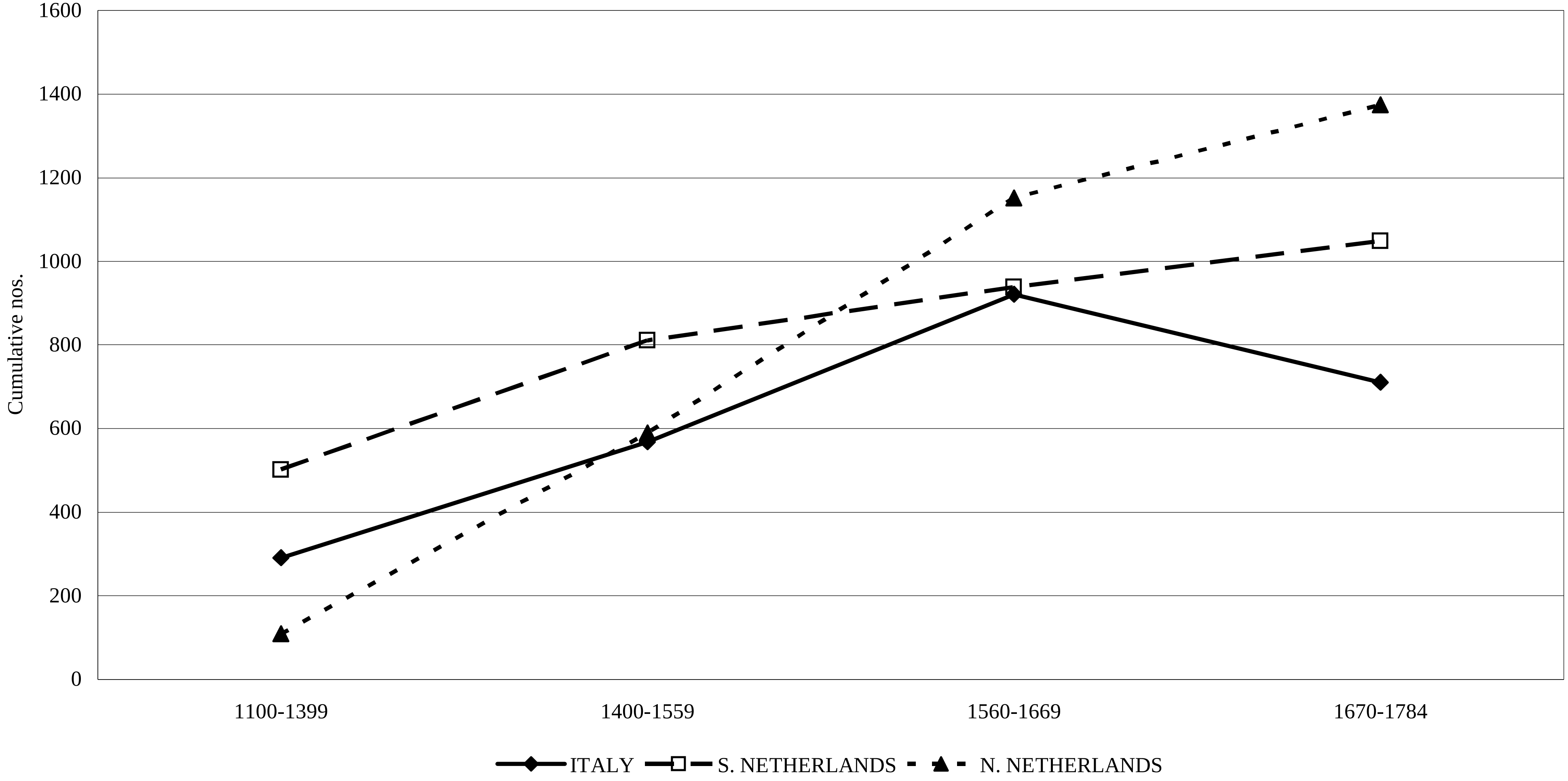
3. COLLECTIVE KNOWLEDGE AND TECHNICAL HEURISTICS

3.1 Knowledge sharing

Although apprenticeship contributed substantially to the collective or 'distributed' nature of premodern technical knowledge, which was an essential feature of technological progress, the inter-generational transmission of knowledge was less important than knowledge sharing—including 'collective invention' (Allen 1983)—between skilled peers.

Technical knowledge sharing between peers took place on site and through migration. Although practices in making, repairing and running machines, building ships and edifices, digging mines, making clocks and watches and so on were necessarily common or accessible knowledge (not least because technicians could not keep reinventing the wheel (Hollister Short 1995), evidence of on-site sharing is more sporadic than for sharing via migrants. The available evidence also relates mostly

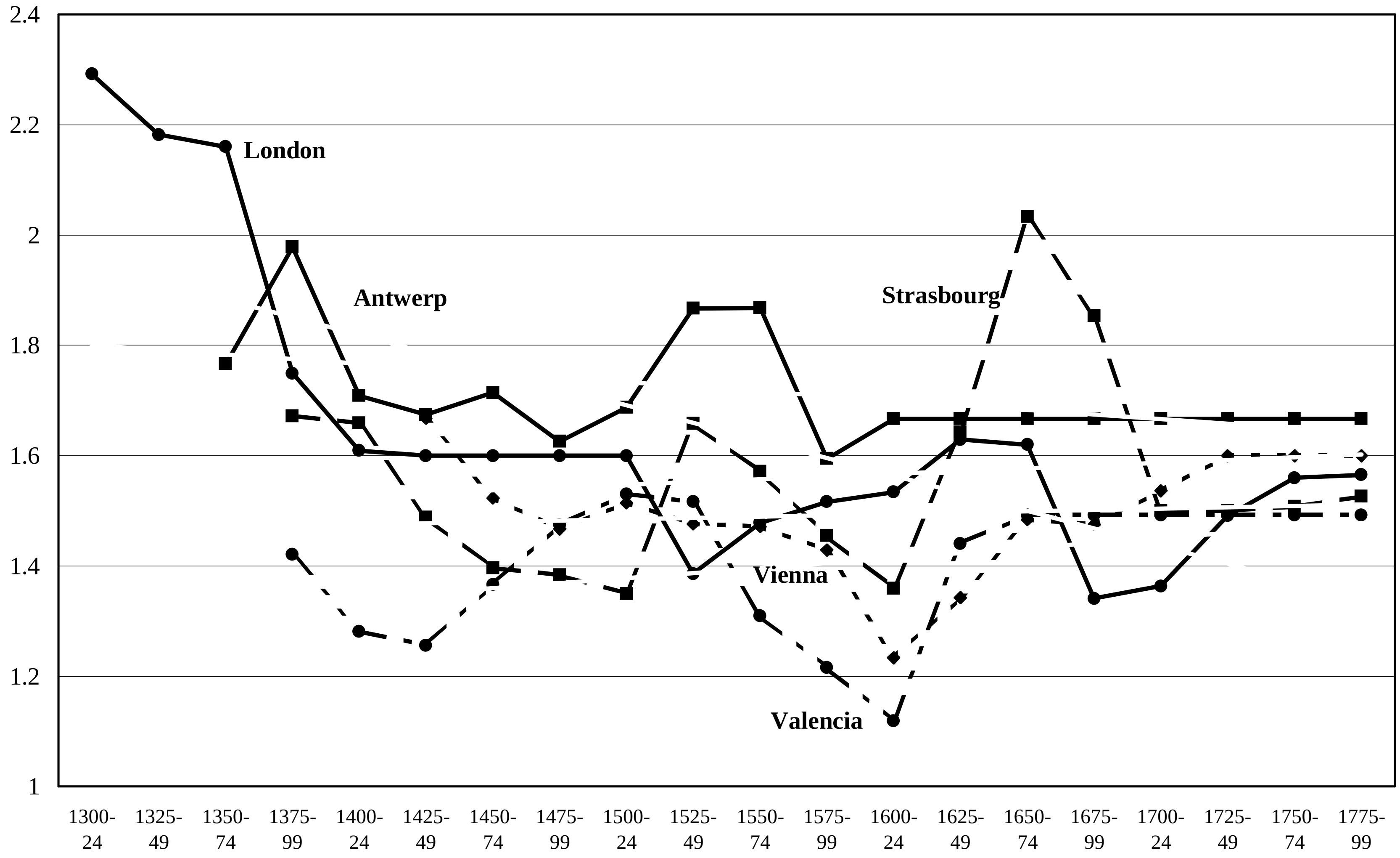
Figure 1. Established craft guilds, Italy and Netherlands 1100-1800



Sources: Angelo Moioli and Jan Lucassen, per litteram.

Source: building masters' wages from Robert Allen's website: http://www.economics.ox.ac.uk/Members/robert.allen/WagesPrices.htm

Figure 2. Skill differentials in the European building industry, 1300-1799 (by city)



to ‘hi-tec’ industries in which competitive pressures and the advantages of cooperation were greatest, and which were therefore most likely to employ foreign workers with new techniques.

In the course of the fifteenth century Venetian glassmaking became one of the most advanced industries in western Europe, comparable in terms of capital investment, specialisation of production, and rate of process and product innovation with shipbuilding, large-scale edifice building, and luxury cloth production (McCray 1999a, 1999b). Discussion of the Venetian guild of glassmakers dwells for the most part on the truculent craft and government policies towards emigrating craftsmen, but this misrepresents the situation in several important ways. First, relations between glassmakers in Venice (Murano) and the outside world were not, and could not be, foreclosed. Already in 1271 the guild statutes deal with the issue of ‘foreigners’ practising the craft of glassmaking in Venice, and the issue persisted into the seventeenth century when Venice finally lost its quasi-monopoly over crystal glass. Second, the production process required an annual closure of 3-4 months during which the workers were in practice free to find work outside the city. Despite the reiteration of fines and even prison terms for glassmakers who left Venice during the dead season, ‘such notices often contained the same names of glassmakers over the years which does not give an indication that the Venetian state’s policies designed to prevent seasonal worker migration were very effective’ (McCray 1999a: 44-5). Worker migration eventually led to the diffusion of Venetian technologies to other European courts and cities; the reason commercial industries took so long to develop elsewhere (in Antwerp, Amsterdam Paris and London) lay with the problems with transferring technical knowledge that was still unable to control consistently for chemical content, and was therefore highly contextual, rather than the Venetians’ ability to monopolise their secrets. Third, Venetian glassmakers made systematic use of codified experimentation in response to consumer demand. Following the decision to ‘rezone’ the industry from the city of Venice to the small island of Murano in 1291, the persistent circulation of skilled workers among the master glassmakers (but the prohibition of poaching), and the speed with which technical innovations were shared and standardized for foreign export, prove that craft technologies, innovations and skills were viewed and acted upon as collective goods.[3]

Beginning again in the fifteenth century, instrument-making (for horology, navigation, land surveying, weighing and measuring, drawing, gunnery and architecture) gradually became one of the most distinctive and technologically innovative industries of premodern Europe. For the most part, these trades were organised into craft guilds. But ‘there was *a priori* no reason why the corporations should frown upon innovation, and they do not seem to have. Major innovations in the structure of clocks and watches such as the introduction of the fusee in watches, the pendulum in clocks, the balance-spring in watches, the jewelling of bearings in watches, new escapements and the development of thermal compensation systems all occurred with little or no guild comment, let alone

[3] However, craft statutes did not regulate the sharing of know-how; this remained proprietary in certain key respects, as shown by differences in the surviving family recipes. The latter offer proof of the kind of ‘competition within cooperation’ sustained by other ‘appropriability institutions’ through time (Merges 2004).

opposition. Similarly the making of new instruments such as telescopes, spyglasses, microscopes and barometers, or new adaptations to old ones, provoked no more reaction than did innovations in methods of manufacture such as the diffusion of wheel-dividing engines and gear-cutting machines, or the invention of a method for the polishing of multiple spectacle lenses in a single operation' (Turner 2007).

The most salient feature of early modern instrument making was in fact the guilds' systematic resistance to individual patenting. One form taken by opposition to patents was to ignore them. In late 1656 the Dutch natural philosopher Christiaan Huygens (1629-95) completed the first clock to employ the pendulum as a regulator. In order to exploit the design he explained it to the Hague clock-maker Salomon Coster, permitting him to take out a an octroy or privilège (the equivalent of a patent) for it on 16 June 1657 that gave Coster the exclusive manufacturing rights for 21 years. By then, however, knowledge of the new timepiece had already spread within the Low Countries and to Paris and Florence. In early 1658 a Rotterdam clock-maker, Simon Douw circumvented Huygens' patent with such success that Huygens abandoned the attempt to enforce the patent in the Dutch Republic. Nonetheless he did try to profit from his invention by obtaining a privilège in France. The request was refused three times by the chancellor, Pierre Seguier, with the comment each time that he did not want to have 'all the master clockmakers of Paris crying after him'. At the same time in London, Ahasuerus I Fromanteel was also constructing pendulum clocks on Huygens' pattern, which he advertised for sale in late 1658.

The French response points to the second form of craft opposition, namely resistance to any patent concession itself. Instrument-makers did not object to innovation, but to giving one of their number a perceived unfair advantage over the others. The standard objection was that an innovation 'was not new, nor his [the patentee's], nor of the use claimed by him', as the London Spectacle-Makers put it in a court case in 1694 against John Marshall, who had got the Royal Society to sponsor his new technology. Fortunately, a few months later Marshall decided to share his innovation with his peers. Between 1685 and 1755, the London Clockmakers' successfully blocked four, and unsuccessfully opposed three out of nine British horological patents; the main objection was that not every innovation was a genuine invention (see also Hilaire-Pérez 1991: 916).

With 143'000 inhabitants in 1789, Lyon was the second largest town in eighteenth-century France. The Grande Fabrique, run by silk merchants in close association with the town authorities, employed nearly a quarter of the population. By changing patterns and fashions on a yearly basis, the Fabrique played an essential part in the success of the silk industry on international markets. But technological progress was also a major concern of local elites. Lyon artisans, who accounted for at least 170 of the nearly 900 inventors who applied to the French national administration for a privilege of invention, were strongly encouraged by the local municipality to develop new technologies, especially new looms. From 1711 the town government, the guild and a representative of the state, the *intendant*, collectively administered a special fund for inventors, the *Caisse du droit des éttoffes étrangères*, paid by a tax on foreign silk entering Lyon. The fund financed innovation from the

research stage to the training of expertise right through to the stage of commercialization (Hilaire-Perez 2006).

The main principle underlying the fund during the eighteenth century was that inventions were a collective good. Most artisans were expected to invent new looms or improve existing ones, display them publicly and sell them to their Lyonnaise peers with no private protection. Exclusive privileges (the Ancien Regime equivalent of patents of invention) were few. Inventing was considered a service to the town and this assumption lay at the basis of the examinations jointly administered by guild officials, members of the Lyon Academy of Sciences and weavers. Then, after a reward was granted, the looms were deposited in the guild's office and artisans would have to create their masterpieces on newly invented looms. Inventors also had to teach their know-how and were rewarded according to the number of pupils they would train. Most grants were indexed by a bonus system on the numbers of new looms actually diffused in town; evaluation and reward were based upon the users' verdict, which encouraged inventors to commercialize their mechanical devices.

These networks were the basis for patterns of innovation in Lyon. Inventive artisans, both weavers and not, were quickly informed of new devices and were constantly striving to improve on them. Indirect evidence that invention was a collective activity is that the new drawing looms, from Falcon's loom to Jacquard's, had compatible programs resulting in cumulatively compatible technology. Vaucanson's programming cylinder was inspired by the Falcon looms that had paper boards passing round a prism (1742). In 1777, a certain Rivet signed one of Dardois' certificates; a few months later Rivet presented a new loom of the same kind. For the building of his second loom, Falcon called upon a weaver, Allard, who in 1763 registered an improvement; Jacquard's invention was also much improved by a certain Breton, a mechanic from the town of Privas.

In the context of the earlier discussion of guilds' hostility towards patents, it is interesting to note that in Lyon day-to-day business practices ranged from free exchange to theft both of skilled workers and ideas. The free circulation of knowledge, including if necessary stealing, was idealised by one of the major eighteenth-century inventors, Philippe de Lassalle, but it seems likely that he was expressing a more widespread opinion. He claimed that he did not condemn the theft of patterns or inventions and that he was pleased when his printed silk cloth was copied and his workers enticed by rivals: 'more than twenty of my colleagues employ hand-painters and entice mine every day as soon as they are trained and they get from them colours and even my own drawings; but I do not complain about these events if they can help to prove that all prejudice against new styles is useless for the common weal and for private business'.

The most extensive evidence of technical sharing over time and space, however, is associated with large building sites, which early on drew skilled workers and engineers from across Europe. For example, the master builder or cleric Villard de Honnecourt stated in his book of drawings (*c*.1215-20) that he settled points with other masters *inter se disputando*—the technical expression for formal debate that had long been standard in the university schools—to underline the fact that his art too rested on firm intellectual principles that could be applied in systematic argumentation. In 1459 master

and journeyman masons involved in building major churches across Central Europe met at Regensburg and stipulated that no-one should be taught for money—with the implication that information should be freely shared (Black 1984: 9). Similarly, the habit of competitive bids for artistic and building projects, well established by the late fourteenth century in Italy and common elsewhere by the sixteenth, assumed that applicants possessed a common core of technical competencies, which patrons could only assess indirectly. Public displays by engineers—which their peers would understand, even if laypeople could not—are recorded from the late fourteenth century, when Giovanni de' Dondi of Padua put his astronomical escapement clock on public show; in the sixteenth century, craftsmen from Augsburg and Nuremberg made rival displays of technical prowess. And, in a letter to Mersenne dated 7 December 1642, Descartes describes the ingénieur Etienne de Villebressieu as 'a very curious man who knew many of those little chemical secrets which are exchanged between members of the craft'.

The strongest proof of on-site knowledge sharing is nonetheless indirect. Once again, some of the most systematic evidence arises in the records of large-scale religious and secular building sites that gave rise to the most complex technical challenges. Church and cathedral building in particular demonstrates both the considerable degree of structural innovation that did take place, and some of its inherent limitations.

The complexity of Gothic cathedrals made it common practice, already in the twelfth century when the first new cathedrals were struck, to call on outside experts to consult on major structural issues. This fact stimulated experimentation—in the use of buttresses, the width of aisle and the height of nave, the height of pier-buttresses and pitch of the roof—that persisted after 1500 when the Gothic style went out of fashion. One measure of such experimentation is the slenderness ratio, that is, the ratio between height and width of the main supporting piers—the higher the ratio, the 'lighter' the final structure. The ratio for the cathedral of Chartres, finished in 1194, was 4.4; thirty years later, at Amiens and Beauvais, the ratio had doubled; by c.1350, at the cathedral of Palma, the master-builders achieved a remarkable ratio of 13.8 (Mark 1978).

As cathedrals grew in height, however, builders faced increasing structural problems. The lower nave, clerestory and roof were subject to increased outer thrust and wind forces, and the foundations were subject to increased vertical pressure and settlement. Since builders lacked a workable theory of structural force before the nineteenth century, they had no means of predicting the structural effects of increased scale. The most frequent solution was to build in modules and to build slowly, observing the evidence of stress over time and making repairs and innovations as needed. The flying buttress was a crucial structural innovation introduced along these lines; 'all flying buttresses in the great northern [French] churches prior to the second half of the twelfth century seem … to have been added as casual expedients only after weaknesses had become apparent or … the vaults had already pushed the walls aside and collapsed'. On other occasions, like the building of Brunelleschi's Florentine dome, 'new structural ideas were deliberately tried out on a smaller scale' (Mainstone 1968: 305).

Achievement of expertise requires the ability to display flexibility with the rules. Major changes to plans were made as the need for them arose, in response to changes in the commission or to structural problems. Thus, when Brunelleschi did not provide workers with a 3-dimensional model for the Florentine Spedale degli Innocenti, the masons and carvers deviated from his design. Originally conceived as a block (*cuadro*) on its shelf in majestic isolation from other buildings, the design of Philip II's palace of the Escorial was gradually extended to include various outbuildings. Twenty years after the start of the building works, 'the artisans were still unsure whether the sanctuary was to be rectangular or apsidal, and [the master mason Herrera] was asked for drawings to clarify the question.' In 1577 'grave doubts arose about the stability of the dome support where the stones were showing fractures. It is reported that public fears caused Herrera reluctantly to reduce the height of the dome's pedestal by 11 ft., and to eliminate the niches, which reduced the mass of the pillars' (Kubler 1982: 82, 98). At about the same time, Venetian architects and masons refused to approve a single plan for the construction of the Rialto Bridge, which was therefore built in stages, with each stage receiving a different plan (Calabi and Morachiello 2000). A century later, Christopher Wren 'adapted the design [of St.Paul's Cathedral] as defects occurred, or his widening experience suggested improvements'. Although as a natural philosopher he developed a wrong theory of arches, as a practical engineer employing little or no calculation he was highly successful, because he employed the heuristics of practical building and engineering (Hamilton 1998).

In conclusion, there is strong evidence that craft guilds—particularly in the more specialised trades—promoted collective knowledge sharing and invention (we shall examine under what circumstances they opposed innovations further below). Conversely, they opposed patenting as a means to privatise technical knowledge and 'damage the trade'. These conclusions raise questions about the type of innovation promoted and hindered by guilds that require additional research. First, we would like to know more about the sources of innovation. For example, individual scientists or savants, who turned to guilded craftsmen to turn their invention into a working machine or to commercialise it more widely, devised some of the most important innovations in horology. However, most of the other innovations discussed here were devised within the craft itself. Second, the relation between guild-based and patented innovations is not entirely clear. Guilds tended to oppose process and product innovations in sectors in which they had competence and which could be viewed as trade secrets, and were more accepting of mechanical inventions in power production (milling, hydraulics and heating), which had high sunk costs and indivisibilities and low reproduction costs. However, the distinction was not clear-cut: Venetian glassmakers, for example, were able to patent some product innovations without major craft opposition. Third, since craft guilds in different urban centers never formally cooperated, technological spillovers had to occur informally through the markets for labour and intermediate goods. It is an open question, if and how these mechanisms constrained the development of more dynamic industrial districts

3.2 Predictability, Codification and Innovation

A less charitable view of the rule bending described previously suggests a *lack of codification*, that is, extreme empiricism and a poor ability to predict. For example, the solutions to structural concerns in cathedral building I described were, inevitably, strongly related to the cathedral's dimensions, such as the ratio of height to width of the nave, and the height and angle of the clerestory and the roof. Gothic dimensions were based on geometrical criteria, which, in northwest Europe, seem to have been largely derived from simple manipulations of the square. Although the rules or algorithms were never fully formulated, they gave rise to specific engineering problems and, thus, to quite specific technical solutions.

Although the development in Gothic building of heuristic 'rules of thumb' or algorithms provided reasonably safe and economical solutions, while reducing computation and design time, it also tended to establish a conceptual identity between building structure and form (Mainstone 1968). This made it hard to transfer the structural theory developed in one Gothic building lodge or lodges in one region to somewhere that had a different ideal form. An instance of the conceptual and technical problems that could ensue occurred at the building site of the new cathedral at Milan at the turn of the fifteenth century. The difficulties arose because Milan at the time was an architectural backwater, and local building skills were inadequate. From the start, therefore, the Milanese asked experts from Central Italy—then architecturally and technically more advanced, yet still peripheral to the Gothic powerhouses further north—to advise them on the form and structure of the new church. Importantly, the plan drawings were based on simple manipulations of the triangle—with the result that the nave and roof of the cathedral were both lower and broader than in the Gothic heartland over the Alps.

Structural problems soon arose, however, so the Milanese brought in North European experts to advise them—with explosive effects. In 1400, Jean Mignot, a master-builder from northern France, insisted on applying his own geometrical design principles to the cathedral's buttresses. 'He argued passionately that only high flying buttresses—a rigorous solution based on *scientia*, that is, on geometrical proportion—could yield a stable structure: "mere craft [*ars*] without rigorous knowledge [*scientia*] is useless"' (Grafton 2000: 268; von Simson 1998). The Lombard masons rebutted that *scientia* without *ars*, without the practical knowledge gained from experience, was equally useless. But the discussion was not, in fact, concerned with either theory or practice taken individually, but rather with the practical links between the two. For Jean Mignot, form (based on *scientia*) defined structure (built through *ars*)—and there was only one legitimate form, derived from the geometrical permutations of the square he was trained in. The disagreement arose because the Milanese preferred another form, derived from a different, albeit equally 'scientific', geometrical procedure. However, they lacked the well-trained, skilled labour to build the related structure and were forced back onto their own local judgment and experience.

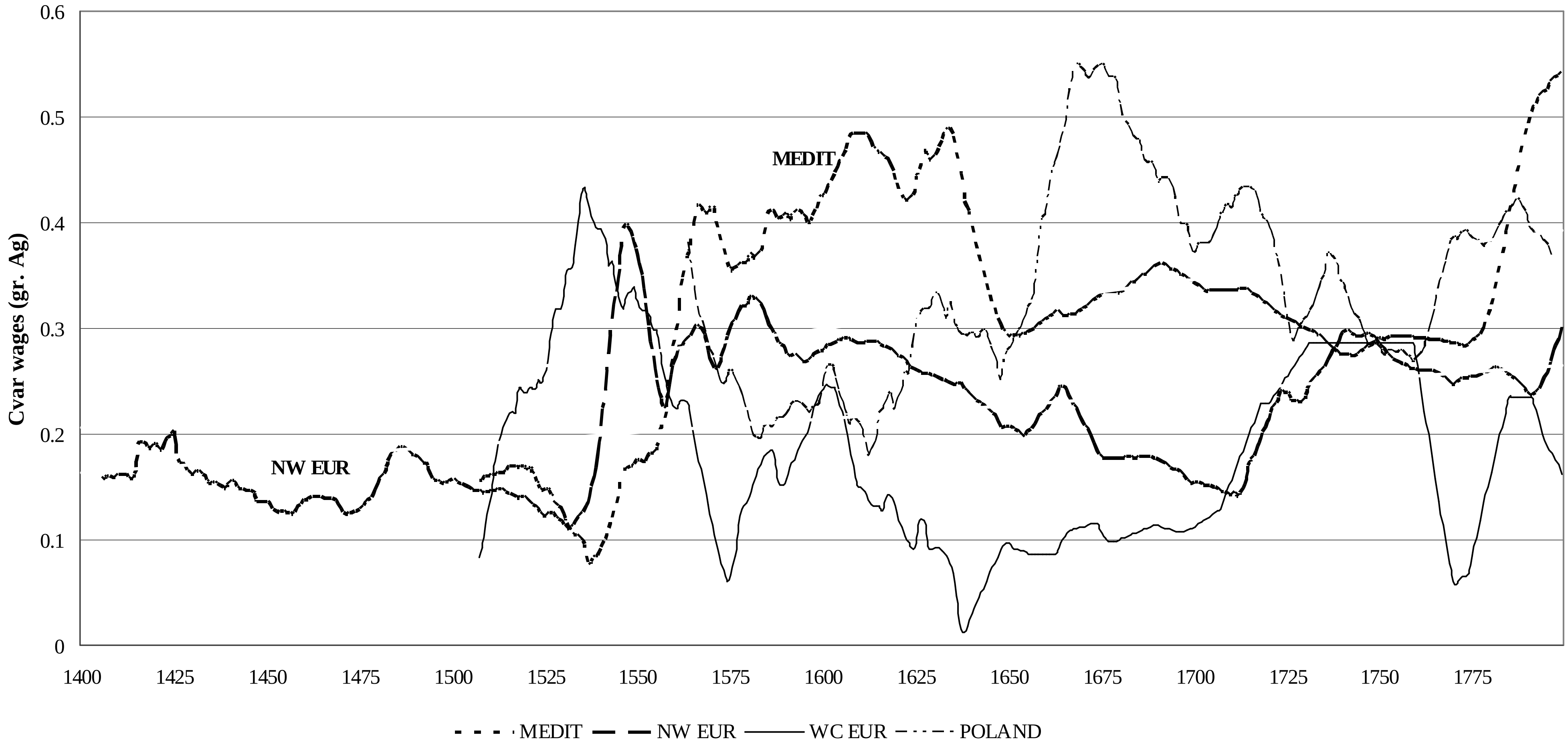
The problem of combining or synthesizing different empirical traditions that did not clearly distinguish between building structure and form could be addressed in different ways. One way was

to codify existing traditions. In the late fifteenth and early sixteenth centurys, several German master masons (Matthäus Roriczer, Lorenz Lechler, and others) drafted detailed notebooks or handbooks that reproduced the square-based configurations of form. The reasons for doing this are not entirely clear, but one relevant factor was probably the increased circulation of masters, journeymen and trainees between Central European building lodges, which must have given rise to confusion and conflict over which lodge tradition would prevail (see **Figure 3** for evidence of strong integration of building wages in Nort west Europe during the pre-1550 era of Gothic building). Although we do not know if the German master masons were trying to synthesise different lodge traditions or if they were simply codifying their local lodges' practice, their actions seem to have been essentially reactive.

The encounter of different technical and design traditions could, however, also generate cognitively new procedures. In sixteenth-century Spain, where tension between Gothic and Italian Renaissance building traditions was particularly lively, the master builder Rodrigo Gil de Hontañon attempted to systematize the design process by creating a sequence of codified procedures to be followed in large church-building projects. Gil's algorithms, drafted around 1540, had three objectives. They aimed to combine Gothic and Classical proportion-based design methods, and to prove their basic identity. They also tried to establish an independent 'science' of structural design. Finally, they attempted to establish new collective heuristics for on-site builders to work with. In pursuing this effort to synthesize and codify two seemingly incompatible aesthetic and building traditions, Gil was led to experiment with Gothic practices on classical arches, and to 'apply new arithmetic procedures to Gothic rib vaults' (Sanabria 1998).

An assessment of craft and engineering heuristics must distinguish between well structured problems, in which situations, operators, and goals tests are all sharply defined, and little specific domain knowledge is needed; and ill structured problems, which require extensive experiential knowledge to be solved effectively through a combination of inductive and deductive processes. Designing buildings, for example, is a poorly structured task. The tests of success are complex and ill defined, and are often elaborated during the solution process. The solution requires flexibility that will often manifest itself as a lack of precision, a 'good-enough' and make-do approach that mathematically grounded theoreticians find disconcerting. Premodern ship-building appears superficially more structured than edifice building, but in other ways it was similarly open-ended: critically, it could not proceed, like building, by testing individual modules as they were built, because success could only be ascertained after the ship was actually launched. The heuristic tools of ship- and edifice building were nonetheless remarkably similar. Like masonry builders, shipbuilders achieved structural stability through a shared, mnemonically rich 'geometric discipline' that legitimized experience gained from building similar structures, and a 'wider tacit or intuitive understanding of the conditions of static equilibrium' based on two components, 'spatial and muscular' (Mainstone 1998).

Figure 3. Integration of the skilled builders' market 1400-1799



Source: see Figure 2.

Venetian shipwrights, for example, based their dimensions on a module that was normally the beam of the proposed galley; this was multiplied in a fixed proportion to give the deck-length, and a fraction of this in turn gave the length of the keel. In addition, the Venetian, or Mediterranean system of module building, was carvel-built. Between the late fifteenth and the early sixteenth century North Atlantic ships, which were previously clinker-built, began to be built according to the Mediterranean system. As the technology migrated, first to Portugal and Spain, thereafter to England and the Hanse area, it changed from its purely tacit and demonstrative form, which employed no graphical support, to a system that relied increasingly on graphical design.

The Venetians had written up their shipbuilding schema already in the fifteenth century, followed by the Portuguese in the mid-to-late sixteenth, but these drawings were purely descriptive and were not used for planning purposes. Proportional design for future planning seems to heve been introduced by the Englishman Mathew Baker in the 1580s, spreading from the 1630s together with 3-dimensional modeling and becoming the norm in England after the Civil War. The French, spurred by Colbert's build-up of the navy, introduced design slightly later but with more sophisticated geometrical methods and tools. These innovations appear to have had two practical implications. On the one hand, planning design may have introduced greater building flexibility. It did not entirely break the link between structure and form, because designers still lacked adequate hydrostatic and hydrodynamic theories; modeling new ships on the basis of experimental drawings was therefore very risky. In the English case, moreover, only part of the hull was designed; the rest was still derived geometrically in the dockyard. Yet even with these limitations, scaled design did offer a more effective way than the algorithm-based Mediterranean system of keeping track of experimentation in the absence of material constraints (McGee 2003).

On the other hand, the use of scaled design made it possible to plan ships with more complex shapes. In the Mediterranean system, a single mould was sufficient to define the whole hull shape (except for the ends). This mould was used literally at midship section and at all sections between amidships, while the end stations (about 10 percent of the ship length from the ends) were constructed on the basis of a rule of curvature or interpolant. Thus the variety of shapes was governed by the chosen midship section and by the few parameters of the longitudinal interpolant, which created section shapes that were close cousins of the midship section and did not permit much curvature. The introduction and improvement of scaled design allowed the English to introduce two interpolants, and the French to design ships with two or more (the number of interopolants defined the number of times the curve of the hull could be changed). This was a typical example of how technological latecomers could benefit from, and improve their predecessors' experience.

3.3 Drawings and Models as Heuristic Devices

Comparison between Venetian and Portuguese ship-drawings, whose sole purpose was to depict established building proportions for non-practitioners, and English and French scaled drawings, which

aimed to establish new proportions for master-builders, suggests that we should not take the nature and purpose of design for granted. Consider the aesthetically stunning plans of Gothic cathedrals, the first of which depicts Rheims cathedral in the mid-thirteenth century, and which seem at first glance to offer remarkably detailed building directions. In fact, many of these plans were presentation copies, drawn after the building was finished; others were drawn for the building commission, and thus differ substantially from the final product; none appear to have been actual working copies, used by the building lodge for practical purposes, because none were actually drawn to scale.

There were two major obstacles to the practical use of Gothic drawings for building purposes. One was the use of geometrical rules in design. This had the advantage of being easily 'portable', since it did not rely on fixed measurements, but the method also generated irrational numbers (such as the diagonal of a square) that could not be easily reproduced on arithmetically proportioned plans. The second obstacle to the use of drawing was, paradoxically, the rediscovery by Filippo Brunelleschi of 3-point perspective in early fifteenth-century Florence, which led his friend Leon Battista Alberti to emphasise the use of 'illusionism in architectural rendering'. As Alberti recognised, however, the perspectival method was of no use to planners and builders. It took three generations of Italian draftsmen to find out how to draw 'plans and elevations, not according to the perspective method but by orthogonal projection, which … permits every element to be shown at the same scale, so that the carpenter and the mason can work from it' (Lotz/Ackermann 1977: xviii-xix). But Alberti's technical effort had another, more desirable consequence (from his point of view), which was to replace the master mason's traditional role as surveyor and planner with the far more prestigious figure of the architect-designer.

Plans, which avoid distortions whilst representing the spatial elements of the object so that it can be reproduced, were nonetheless practically unknown outside architecture before the seventeenth century. In particular, the pictorial or illusionistic method persisted in the drawing of machines. Although the degree of sophistication of machine representations grew markedly over the period between the early thirteenth-century sketches by Villard de Honnecourt and his colleagues, the fourteenth century designs by Guido da Vigevano, the fifteenth century drawings by Brunelleschi, Francesco di Giorgio Martini and Leonardo, and the sixteenth-century representations of mining machinery in Georgius Agricola's *De re metallica*, they were all in one way or another 'false plans', inasmuch as they left size, proportions and many essential details, undefined (Lefèvre 2003).

The first systematic, measured plans of machines are, as we saw, those of English ships. Yet, as with architectural drawings, the development of graphic design in shipping may have been more a strategic element in the cultural and functional separation between designers and builders, than a genuine cognitive advance in the making of premodern ships. Certainly, the analogy raises the question—which cannot be addressed here—of the cognitive significance of graphic design for technological progress. One may simply note, that although the introduction of planning design undoubtedly allowed greater flexibility in designing form, be it the form of buildings or the form of a ship, it is not self-evident that design effected a clear improvement for innovation in structure.

From the late Middle Ages technicians were more likely to use 3-dimensional models in wood, clay, and gypsum to convey information about machines (including buildings), and to test their performance. Like drawn plans, 3-dimensional models have two distinct uses: 1. to store information and to help communicate it from one person to another (e.g. designer to client, builder or supplier); 2. to help produce in the engineer and client the necessary level of confidence that the proposed structure will work and can be built (Addis 1998a). Although the use of 3-dimensional building models is attested as far back in time as Babylonian Mesopotamia, it became a more regular documented practice only in fourteenth-century Tuscany; a century later the use of models for building purposes was mentioned as a matter of established practise in architectural treatises by Leon Battista Alberti, Antonio Averlino, and Francesco di Giorgio Martini, with Martini making the cognitive aspects of model-building explicit: "Whereas it is difficult to demonstrate everything through drawings, nor is it at all possible to express many things in words, … so it is necessary to make a model of nearly every object" (Martini 1967: 1, 142). Soon after 1500 the usage of building models spread to southern Germany and France, with the English following about a century later.

Far less is known about the related practice of making scaled-down models of working machines. The earliest reference to a mechanical model is found in a late fifteenth century description of a new wire-drawing machine invented in late fourteenth century Nuremberg (Blake-Coleman 1992). A few years later, in May 1402, the master masons at Milan cathedral were asked to inspect sketches submitted in a contest to find the best mechanical device for sawing stone blocks "without manpower"; the most promising design was then to be realised in the form of a wooden model in reduced size, suggesting a well-established combination of sketch-based and 3-dimensional mechanical planning, experimentation, and demonstration of expertise (Popplow 2002).

By the early 1500s scaled-down models were being used both in engineering competitions and for applications for technical patents. Models were commonest until the mid-sixteenth century in the two most advanced industrial regions of the time, north-central Italy and southern Germany, but thereafter they began to be used also in Spain and France. In the early decades of the sixteenth century a Nuremberg craftsman made a "nice wooden design for the king of England, about one *Ellen* long, in which one water wheel drove mechanisms for grinding, sharpening, polishing and fulling", but this may have been an article for the king's private collection (Popplow 2002: 12); 3-dimensional models are first recorded in English ship-building in the early seventeenth century.[4]

[4] After the late sixteenth century models of machines increasingly became collectors' items in Kunstkammern and articles for mechanical demonstration in the private homes of engineers and the public estabishments of scientific academies and engineering institutions. Model-based testing was central to the work of eighteenth-century engineers like Christopher Polhem (1661-1751), Antoine de Parciewux (1703-68) and John Smeaton (1724-92). In the same years, in a curious inversion of their origins in craft and engineering practice, reforming technical institutions briefly adopted machine models as a means to teach apprentices craft skills without submitting them to craft-based training.

3.4 Experimentation

Despite the documented use of model machines from the 1300s, evidence of technical experimentation in premodern Europe is irregular and rarely indirect; some of it was reported previously in discussing building practices. It was exceedingly rare for inventors, tinkerers, or technicians to write in any detail about their activities (as opposed to their speculations, like Leonardo) before the eighteenth century. However, two unusual sixteenth-century texts do shed light on kinds of experimental practice that under normal circumstances left no material trace, namely machine and chemical testing.

Some of the earliest evidence of individual testing and experimentation comes from the Venetian glass industry. According to local tradition, Angelo Barovier was a Venetian glass-worker who during the 1450s invented new kinds of glass—crystal, *lattimo,* chalcedony and *porcellano*—which rapidly became the base for the siuccess of the Venetian glass industry throughout Europe. In fact, he seems to have been 'an owner of a glass shop who carried out experiments purposefully intended to produce new glass compositions'. He was a friend of Paolo da Pergola, a humanist-philosopher who taught in Venice and lectured on 'the combinations and transformations of metals'; and a book published in 1500 states that Angelo took 'the fruit of this speculation and put it into practice'. There is also documentary reference to what appears to be a series of experiments by the Barovier, Mozetto and d'Angelo families into these new types of glass in 1457 and 1460. As this suggests, Angelo Barovier's successes were not the work of a solitary genius, but the outcome of a series of small-scale innovations stretching over the preceding century that included, most crucially, the purification of the *alume catino* ash that increased the amount of sodium (Na_2O), and the discovery of an as yet unknown material that reduced the problem of *cristallo* glass corrosion (McCray 1999: 98-100, 115). Although it is unclear if these early experiments were recorded in writing, the first known reference to a recipe book dates from 1446, and we know—because they survoive—that by the sixteenth century it was normal practice for family-based glass-making firms to keep their own books of recipes or 'secrets'.

The description by Giuseppe Ceredi, a Paduan engineer, of his invention (or rediscovery) of Archimedean water-screws for drainage and irrigation purposes contains what may be the first suggestion in print to build models at different specifications in order to optimize machine-building. Here is Ceredi's description: 'I was able to fabricate a great many models, small and large, adding, changing, and removing various things according to the condition of the material, or the grouping of many primary and secondary causes, or the variety of the mediums, or the proportions, or the force of the movers, or many other obstacles that hinder the thing sought. For it is well known by scientists [*scientiati*] that when things are put in operation, so numerous and great a heap of observations need to be kept in mind all together to hit on any new and important effect that it is almost impossible to fit them all properly together'. Having found that no uniform rules could be found concerning the optimum construction of water-screws, he ultimately determined that the best procedure would be to

use a screw about 8 m. long, to raise water about 5 m. Ceredi was aware of scaling problems with machines, and proceeded accordingly. ‘To put this into execution’, Ceredi stated, ‘and have it based firmly on experience as guided by reason, it was necessary to make a large number of models, both small and large, now with one length and height of channels and now with another, in order to be able to proportion the whole to the mover [the screw] and to its organ [the crank].”

At about the same time, the French potter Bernard Palissy described how, over ten years, he slowly mastered how to combine the quality of clay, the pot’s thickness, the melting point, type, quality and colours of the enamel, the level and constancy of fire, and the pot’s position in the kiln to make Italian-style enamel (Fayence) (Palissy 1996). Although narrated in the form and with the tropes of Reformed Christian salvation, the tale of Palissy’s struggle to control for the many variables of pot-making rings true in reminding us that in chemical processes, visual and 3-dimensional models were of little use. Positive results could only be gained through an approach on the borderline between alchemical and craft practice, exemplified also by the recipe books for Venetian glassmaking. It is all very well to define the ‘scientific method’ as ‘accurate measurement, controlled experiment, and an insistence on reproducibility’. As Palissy noted, the problem with this ideal, to which in principle he subscribed, was to know *what* to measure and experiment with—something scientists would be no better at defining for nearly three centuries thereafter. So recipes were the solution—but recipes, as opposed to machines, were hard to transfer, because their results depended critically on a combination of material ingredients, and atmospheric and other conditions that could not be easily controlled for, and thus, easily reproduced.

In sum, evidence of technical heuristics, codification, and appropriation shows some of the ways *how* existing and new craft and engineering knowledge was shared or ‘distributed’. However, knowledge sharing was more likely and more intense within large-scale, hi-tec or high-value sectors like ship- and edifice-building, mining and metalworking, the making of clocks and scientific instruments, gold-smithing and silk weaving, and glassmaking, industries which displayed strong division of labour and advanced levels of coordination and where cooperation provided either clear economies of scale and scope or marketing advantages—many of which are also notable for having played the most technologically innovative role in the Industrial Revolution.

4. SPATIAL TRANSFER OF TECHNICAL KNOWLEDGE

4.1 Texts and Patents

Thus far we have focused on how premodern technical knowledge was codified and shared. In order to fully answer the initial question of how premodern technical innovation was generated and sustained, we must also address the matter of how technical knowledge travelled.

In theory, technical knowledge could be disseminated across space in three ways: through publicly available texts, through patents, and through migrating individuals. In practice, published,

‘disembodied’ technical knowledge did not disseminate well, as John Harris, a lifelong student of technological transfer between eighteenth England and France, concluded: ‘the craft nature of virtually all the technologies … meant that written descriptions and plans and drawings were only marginally useful’ (Harris 1998: 549).

Premodern technical writers seldom practiced what they described, and so typically overestimated the role played by explicit, propositional knowledge in craft and engineering practice. Written manuals were incomplete and sometimes misleading; they might contain technical details not actually applied in solving the problem; and they left out crucial practising ‘tricks’. Such problems were compounded by the difficulties faced by experts in describing what cues they responded to and what factors contributed to their decisions. An investigation on the training of Spanish ship pilots for the Indies defended their alleged incompetence as follows: 'even though a person is not very resolute in responding to the theory, [yet] he understands it well, and he who has experience understands it if he acts correctly, and *there are many who don't know how to propose or explain how to use an instrument, but with one in their hand use it very well'* (Sandman 2001: 276; my emphasis). The large tacit and non-linear component of experience-based knowledge explains why equally skilled experts in the same field disagreed on how to do their job (Ash 2000), and why not a single premodern innovation was transferred through print alone.

The most popular and sophisticated manuals, architectural treatises, were searched for formal motifs rather than for building techniques. The woodcuts in the most famous and extensively copied treatise, by Andrea Palladio (published 1570), were drawn in orthogonal projection and therefore may have made it possible for architects to study building proportions; however, they gave little indication of construction methods or the use of materials, for Palladio like other treatise writers assumed that architects and builders would adapt his designs to local building traditions and to the availability of materials (Trogu Rohrich 1999). Part of the popularity of Palladio’s treatise arose from this inherent flexibility. By contrast, most readers would have found the technical information on construction difficult to decipher from the illustrations alone. The English architect Inigo Jones, for example, learned the design principles of the orders and the fundamental planning issues of domestic architecture on his own; since he was not trained as a mason or carpenter, however, he needed to speak with workers and architects in order to learn practical building techniques. Between 1613 and 1614 he traveled to Italy for this purpose; on meeting the architect Vincenzo Scamozzi, Jones asked him for help with the technical aspects of vaults, noting in his diary: “Friday the first of August 1614 spoake with Scamozo in this matter and he hath resolued me in this in the manner of voltes”.

Premodern patents faced similar technical and cognitive problems. Patent law was first established at Venice in 1474 and spread rapidly either in law or in practice to the rest of Italy and northwards, first to the German principalities, then to France, Spain and the Low Countries, and subsequently to England (Frumkin 1947-49). By contrast with their modern counterparts, however, premodern patent laws did not require novelty and originality; most patent descriptions were generic and did not remotely approximate a modern blueprint; and innovations were seldom examined

systematically before the eighteenth century. Although some administrations, like Venice from the early sixteenth century, demanded a working model of patented machinery, inventors working on models were frequently unable to overcome scaling problems with full-sized machines, as noted by Giuseppe Ceredi in 1567 (Ceredi 1567: 52; Drake 1976). The problems arose particularly for large-scale mechanical inventions involved in power generation (milling, hydraulics, heating). In practice, patents were a means for towns or rulers to encourage the introduction of a new machine or process in their jurisdiction, by conceding a contingent monopoly over exploitation. Patents were also used as a means of commercial advertisement. Since patents tended to require costly lobbying and upfront fees, and placed the entire burden of proof and investment risk on the inventor's shoulders, barriers to entry to the technology market via patents were generally high.

The propensity to patent was also affected by other factors. One was that, as in modern economies, 'only unconcealable inventions [were] patented' (Machlup and Penroes 1950: 27; Bessen 2005). Many product and process innovations were never patented because they were better protected as trade secrets or because they were part of the collective knowledge of a craft; for example, the makers of watches, clocks, and astronomical and other scientific instruments, most of who were organised in guilds, opposed patents that tried to privatise knowledge that was already in the craft's domain or that were perceived to restrain trade (Epstein and Prak 2007). Consequently, premodern patent rights seem not to have played a major role in innovation before 1800 (MacLeod 1987, 1988; Molà 2004).

The assumption that patent rights to invention were necessary for premodern technological innovation rests on the view that intellectual creation is nonrivalrous, and that once in the public domain, it can be copied at no additional cost. This fact may be true but is economically irrelevant, since what matters is the application of the new idea, which has learning and physical costs. In premodern manufacture, the costs of application arose from the largely implicit nature of technical knowledge, which created the need for one-on-one training and meant that technological innovations had to be transferred by travelling craftsmen and engineers.

4.2 Transferring Skilled Technicians: When and Why Did Craft Guilds Oppose Technical Innovation?

In practice, technological transfer could only be successfully achieved through human mobility. However, successful transfer faced several obstacles. The most oft-cited, trade secrecy and guild opposition to innovation, were also the least important.

As the previous discussion of technical heuristics makes clear, most so-called craft secrets were in fact open to anyone willing to train in the relevant craft and engineering practices. For example, although 'Gothic' geometrical principles for drawing elevations—developed around Paris between mid-twelfth and mid-thirteenth centuries—were said to be the closest guarded masons' 'secret', they were actually shared by every trained mason north of the Alps. The application of Gothic

principles was simply a practice that distinguished trained masons from everyone else, and there is no evidence of technical exclusivism (Shelby 1976; Fernie 1990). Similarly, the distributed character of technical knowledge—institutionalized through apprenticeship, guild practice and division of labour, and the systematic circulation of skilled labour—meant that genuine technical secrets were hard to keep, if they were deemed useful.

The belief that crafts were vowed to secrecy and exclusivism appears to have originated in the seventeenth century among the 'new scientists' and natural philosophers. Fascinated by technicians' proven empirical knowledge of the material world, empirically-oriented intellectuals between the late fifteenth (Leonardo) and the early seventeenth century (Bacon, Galileo, Descartes) wrote admiringly about craft practices and craft knowledge. But their admiration was tinged with suspicion. They were unable to understand technical knowledge without extensive practice, and being unaware of the cognitive reasons for this, they found it hard to believe that illiterate or near illiterate technicians could know more about nature than they did. Thus, for example, reports of Royal Society experiments never name the technicians who actually made and maintained the instrumentation and performed the experimentation (Shapin 1988).

Second, the new scientists wished to distance themselves forcefully from the long-standing tradition of alchemy, which they associated not wholly justifiably with a strong desire for secrecy and with social and technical exclusivism (Newman 1998, 1999, 2000). In this the new scientists followed the Scholastics, for whom 'knowledge of [alchemical] secrets was strictu sensu impossible: they could be experienced, and could be found out 'experimentally', but they could not be understood or explained according to the canons of logic and natural philosophy' (Eamon 1994: 53). During the sixteenth century alchemists such as Paracelsus, Girolamo Cardano, and Andreas Libavius deliberately associated their practices with craft activities and methods in order to emphasize their empirical, non-scholastic approach. Seventeenth-century new scientists were thus offered a ready-made conceptual framework, which stressed secretiveness and unreliability, into which to slot craft practices, and which moreover drew attention to the scientists' self-declared intellectual openness.

The third strand in the scientists' emerging theory of craft practice arose from the new scientists' concern with establishing a readily transportable method, whose principal aim was to codify the facts of the natural world into a universal language. This set them explicitly at odds with technicians, who they described as having no method at all: this was of course a misrepresentation, for codification was also important for technicians, albeit as a means to the end of making things that worked rather than an intellectual end in itself.

The claim that guilds systematically opposed outside innovations is also problematic. One reason is that it is excessively generic. If it is meant to say that guilds never innovated, it is, as we have seen, demonstrably false. In addition to European instrument-making, Venetian glassmaking, and Lyonnais silk cloth production, studies of premodern guild subcontracting (Lis and Soly 2006) and of Dutch painting in the Golden Age (Prak 2006) are equally conclusive on this point. Patterns of patenting in sixteenth-century Italy also show that guilds were in the forefront of testing and

introducing technical innovations (Molà 2004). If, on the other hand, the claim is meant to say that guilds would at some point become technically conservative, it loses any predictive value. The argument is also methodologically naive. Although it assumes that all innovationsat were refused were better than current practice, the record seldom reveals whether guild opposition was driven by rent seeking or by an objective assessment of the innovation's merits.

Individual instances of resistance to change tell us little about relations between the guilds and technological progress in general. A theory of guild innovation must identify both the *technical* and the *political* criteria that dictated the choice of technology and established a given technological path. In principle, one would expect the crafts to prefer technology that privileged skill-enhancing, capital-saving factors. Despite a lack of systematic research, evidence from patent records indicates that this was precisely the kind of innovation that prevailed in England before the mid- to late eighteenth century, when the country's guilds were still very active. Between 1660 and 1799, labor saving innovations accounted for less than 20 percent of the total, whereas innovations aimed at saving capital (especially working capital) and at quality improvements accounted for more than 60 percent. There is no reason to believe that patterns elsewhere in Europe were very different (MacLeod 1988: ch.9; Griffiths, Hunt, and O'Brien 1992: 892-95).

The response to innovation by individual crafts depended primarily on political rather than market forces. There was a fundamental difference in outlook between the poorer craftsmen, who had low capital investments and drew their main source of livelihood from their skills, and who therefore (frequently in alliance with the journeymen) opposed capital-intensive and labor-saving innovations, and the wealthier artisans who were less threatened. Relations between the guild's constituencies and the state also affected decisions. On the one hand, the wealthier and more innovative masters were more likely to influence government policy, and under normal circumstances authorities seem to have allowed them to circumvent guild regulations. On the other hand, city councils were more willing to meet the small masters' concerns if labor saving innovations coincided with a serious economic downturn, both to ensure social and political stability and to restrain unemployed craftsmen from leaving the town. In other words, guilds were most likely to act as "recession cartels" when economic circumstances took a turn for the worse, but they still required political support to enforce cartel restrictions successfully against free riders and competing guilds. Thus, Dutch guilds began to resort systematically to restrictive policies when the country entered a long phase of stagnation after the mid-seventeenth century—but only after obtaining municipal approval (de Vries and van der Woude 1997: 294, 340-41, 582; Unger 1978: ch.5). Similarly, craft guilds reacted very differently to the introduction in the seventeenth century of a major technological innovation, the silk ribbon loom, according to their political situation within town and region, the competition from neighbouring industries, the degree of internal stratification and their regulatory capacities. Their response to a labour saving and deskilling technological innovation was depended on external and internal market structures (Pfister 2006).

4.3 Transferring Skilled Technicians: How Did It Work?

Although most technical knowledge remained either unformulated or unrecorded, one should not confuse the absence of written texts detailing technical practice with technician's fundamental commitment to secrecy. Rather, the absence of texts is evidence that writing (including, for many purposes, drawing) was a highly ineffective mode of transmission. As Palladio's work suggests, useful or experiential knowledge—knowledge that works—is, in principle, local. This does not mean that it is necessarily secret, or that it remains in an individual's head: premodern technical knowledge was extensively socialized and shared. Some elements of experiential knowledge—in shipping, and to a lesser extent in building—were increasingly codified in writing and drawing. A partial result of textual codification was to make local knowledge less local, accessible both to the emerging professional categories of designers and, in principle, to makers outside the original community of practitioners. Other experiential knowledge was embedded in objects, and objects could travel and be observed: ships could be seen, clocks could be taken apart, imported Chinese porcelain could prove that something deemed impossible, or unknown, could in fact be done.

Strong evidence as to the effectiveness of technological transfer through migration comes from the observation, discussed previously, that technological leadership moved over time from southern to northwestern Europe—from Italy (1200-1450), to the southern Rhineland and southern Netherlands (c.1450-1570), to the Dutch Republic (1570-1675) and finally to Britain after c. 1675—largely thanks to skilled individuals trained by guilds or by other communities of specialized technicians (miners, builders, shipbuilders etc.).

Between c.1300 and c.1550, European craft guilds and polities devised institutional arrangements that sustained skilled workers' mobility and raised the *potential* rate of technological innovation. Skilled migrant workers included mainly apprentices and journeymen, who travelled on a seasonal basis, or established masters, whose migrations were more often permanent (see **Maps ****). More systdematic apprentice and journeyman mobility was an outgrowth out of the temporary skills shortages that followed the plague epidemics of 1348-50. By 1550 tramping was common in much of Western Europe, although it was only fully institutionalised in German-speaking central Europe from the sixteenth century and less extensively in late seventeenth- and eighteenth century France. In England, independent journeyman organisations seem to have been formed after the decline of London as a national training centre from the 1680s. Since the main purpose of organised tramping was to coordinate information and allocate skilled labour more efficiently across regions, formal organisations never arose in densely urbanised regions like northern Italy and the Low Countries where information costs were low (Epstein 2004; Wildasin 2000).

Apprentice and journeyman mobility helped develop and diffuse technical knowledge within areas that were on the whole institutionally, economically and culturally similar or adjacent. The main source of innovation in the late Middle Ages was Italy, and the main initial recipients, southern and central German-speaking territories. Cotton weaving, for example, was transferred to Germany from northern Italy in 1363, and by 1383 already its wares were being sold in large quantities on north

European markets. One of the first cotton weavers—a ‘cotton-maker’ (*parchantmacher*) – is mentioned in Nördlingen in 1373, and ‘Milan’ and its declensions are frequent among the earliest weavers’ names—although the transfer was probably also facilitated by German merchants or by the return home of German weavers who had learned the craft in Genoa, Venice and Lombardy (von Strömer 1978: 20, 31, 142). Following the craft’s speedy diffusion in upper Germany, regional industries there established the central European standards in cloth types and qualities, to which east German production conformed following the large-scale migration of upper German weavers to Leipzig between 1471 and 1550. Many east German towns adopted the Augsburg ordinances on cotton, and it is said that the flourishing of guilds in the region dates from the time ‘when the Swabians came flocking’ (Aubin and Kunze 1940: 34ff.).

A first phase in diffusing the public clock occurred in 1370-80; by 1400 all major towns had their public clocks; and by 1500 the innovation had spread across the whole of Europe, albeit entirely thanks to migration of technical experts (Dohrn-Rossum 199?). The diffusion of papermaking in central Europe also relied on help from central and north Italian craftsmen. The hugely successful spread of book printing—which had been a purely German affair until 1465—was based on wandering printers and craft experts; already by 1472 Germany was importing Italian book characters via returning German printers. In the sixteenth century, thanks to Venetian migrants, transparent (‘Venetian’) glass began to be produced throughout central Europe.

The chances for apprentices and journeymen of accumulating technical skills and knowledge probably stood in direct relation to the length and radius of the tramping experience. Journeymen who travelled widely learned about regional differences in work organisation, and came to recognise different practices, raw materials and products. The clearest evidence that itinerant journeymen could acquire additional technical skills comes from the existence of bans on migration, as among Venetian glassmakers and Nuremberg metalworkers. Nuremberg tried to protect its technical primacy in the metal industries by banning any kind of emigration: apprentices had to swear not to practise their craft anywhere else, journeyman tramping was forbidden, and to avoid the poaching of workers, masters and employers had to ply them with work and ‘not allow them any holidays’, or if necessary, provide them with holiday pay. Every so often Nürnberg’s town council proceeded against crafts like the wirepullers, which allowed journeymen to be lured by outsiders to whom they divulged manufacturing secrets. Over time, however, the lockout became counter-rpoductive, inasmuch as it hindered Nuremberg craftsmen from traveling and acquiring new techniques elsewhere.

Nascent monarchies and territorial states made it a point to attract new skills and technology from beyond adjacent regions. International competition for skilled workers, for example for master cathedral builders, existed already during the Middle Ages, but it increased markedly during the early Renaissance (c.1450-1550) in the western Mediterranean, and after the Reformation in north-central Europe, when European rulers made it policy to attract displaced craftsmen from enemy lands (**Map ****). The expulsion of the Jews from Catholic Spain and southern Italy in the late fifteenth century; of Walloons and *Nederduits* from the Habsburg Netherlands between the posting of Luther’s Theses

(1517) and the Treaty of Westphalia (1648), which scattered about 100’000 skilled technicians and merchants across northern France, England, Germany, Poland, Scandinavia (especially Sweden), and the Dutch Republic; and of the Huguenots from France to, especially, Geneva and England after the Revocation of the Edict of Nantes (1685) are just some threads in a complex web of treligiously and politically driven technical diffusion (Schilling 1991; Scoville 1953; Scouloudi 1985) (**Map **)**.

From the mid-seventeenth century, mercantilist states engaged in an increasingly systematic promotion of domestic industry via industrial espionage and more deliberate and focused immigration policies; attempts by guilds and political authorities to stop skilled workers from migrating were stymied by weak administrations, state competition, and the increased circulation of correspondence, men and equipment (Roche 2003; Harris 1992).

Each passing of the technological torch set in motion a period of rapid innovation in the new regional leader. Although technological leadership is hard to establish for this period, two measures are available. One is the technology of energy production, as suggested by Karel Davids, which expanded and improved systematically during the priod we are concerned with, from timber (Ancient and medieval Mediterranean) to advances in water power (fifteenth-sixteenth century Southern Germany), from the extensive use of peat and, especially, wind (seventeenth-century Dutch Republic) to the systematic use of coal (seventeenth- and eighteenth-century Britain). Another measure of technological leadership is the production of scientific and timekeeping instruments, which followed roughly the same course, from Italy northwest to Britain—with a detour through sixteenth and seventeenth-century Paris in the case of instrument making.

Being at the right place at the right point in time could be transformative. Britain, for example, was a one-way technological debtor up to the late seventeenth century; between 1600 and 1675 it imported from the Continent the most advanced techniques in metal smelting and forging, in the making of glass, pottery, guns and watches, scientific instruments, gold-smithing, wool, linen and silk cloth, and in hydraulic engineering and agriculture (Hollister-Short 1976; Mitchell 1995). The country’s position of dependence began to be reversed after c.1675, and already by 1720, the English Parliament had become so confident in native technical abilities, and so worried about international competitors, that it passed a law banning the emigration of resident technicians.

The two main impediments to technological transfer were thus information and transport costs, which restricted labour mobility, and the absence of a local skills base that could successfully apply incoming techniques. Exogenous innovation could be absorbed only if an adequate supply of technicians able to apply the new techniques was available: a major hurdle with transferring British coal-based technologies to non-coal based Continental economies in the eighteenth century, for example, was the incompatibility of the associated intermediate goods, parts and skills (Harris 1978). Transmission of the most up to date knowledge could therefore be excruciatingly slow. It took over a century to transfer Hollander paper beaters from the seventeenth-century Netherlands to eighteenth-century France because of a lack of good machine makers and repairers; eighteenth-century French metalworkers—who, significantly, were not organized in guilds—had no knowledge of high quality

steelmaking that had been practised in Germany, northern Italy, Sweden and England for up to two centuries before (Rosenband 2000; Smith, 1956).

Bottlenecks to technical transfer were relaxed over time by falling information and transport costs, which can be proxied reasonably accurately by trends in urbanisation, and in financial and other market integration (Bairoch, Batou and Chèvre 1988; Epstein 2001; Neal 2000; Persson 1999). The most salient example of the correlation between technological leadership and urbanisation is premodern England, which was transformed between 1650 and 1750 from a technological and under-urbanised semi-periphery to the most technologically innovative and urbanised country in the West. The most plausible reasons for the correlation are the standard Marshallian ones: economically successful towns attract skilled workers, whose pooling stimulates the growth of specialised intermediate goods industries; knowledge spillovers among firms increase; and reliable knowledge improves and increases with use. This model fits well with the evidence that premodern regional technological leadership followed commercial leadership, with a certain lag (Davids 1995).

5. CONCLUSIONS

Notwithstanding the absence of much written evidence, evidence from technical practice suggests that premodern non-scientific technical knowledge expressed significant degrees of abstraction, experimentation and cumulation. There is also strong evidence that premodern technicians codified heuristic rules in response to growing pressure for standardization and rising mobility of skilled workers. Finally, the process of codification was dynamic, in two ways. On the one hand, the technology of codification was improved and its usage vastly extended over the period under consideration. Printing played a role in this, but it was arguably less important than the falling cost of paper to draw on. On the other hand, to an extent we still barely understand, the process of codification was cumulative. Drawings, models, recipes, and lists of proportions could circulate independently of their authors and outlive them, although it still required experiential knowledge to interpret them.

Premodern technical progress was sustained and limited by the manner by which generic technical knowledge was codified and by ‘collective invention’ (Allen 1983; Epstein 2004). Premodern technical codification faced three important cognitive limitations, which it shared in several ways with contemporary natural philosophy. First, premodern technicians, like seventeenth and eighteenth century natural philosophers and their modern counterparts, faced the problem that tacit knowledge—both ostensive knowledge, and knowledge inexpressible in natural language—is ubiquitous and unavoidable; thus, written codification was and is, by definition, always incomplete. Second, premodern technicians, like natural philosophers, faced the problem that some kinds of knowledge were more easily codified and transferred—via proportions and ratios, diagrams, models and ‘recipes’—than others. Thus, technical knowledge related to chemistry and metallurgy was harder to mobilize, because the character and quality of inputs was more variable, and because the final

product could not be easily 'reverse engineered' to reveal its underlying manufacturing process (Klein 2005). Lastly, premodern technology's empiricism made it hard for technicians to distinguish clearly between theoretical structure and form; a similar difficulty may explain the inability of most premodern natural philosophy to generate technologically fungible science. Technicians extrapolated experiential knowledge from empirical observation of what worked within a given set of material circumstances and practices. They produced second order codifications of practice, rich in information, able to capture a high degree of variance in information, but possessing limited predicitive powers. Although practices and practice-based algorithms gave broad scope for technical improvements, they offered little information on how a set of rules with different premises would affect a known technical process. In other words, each set of rules came with a corresponding bundle of practices.

In principle, the weak distinction between structure and form, between rules and practice that we saw at work in cathedral and shipbuilding, raised the costs of switching from one set of rules to another. In practice, however, these constraints were less serious than those coming from restrictions to information flows, for there is no reason to believe that most premodern technologies, based on empirical practices and available materials, had reached their technical frontier even by 1800. The most severe restrictions to premodern technological reliability and innovation arose from the high information and reproduction costs related to experience-based knowledge. The principal source of diminishing returns to technical knowledge seems to have been the cost of communication between dispersed craftsmen and engineers, rather than the narrowness of the premodern crafts' epistemic base.

Although in principle tacit knowledge should have raised the appropriability of rent streams from invention, in practice appropriability was rather low, because the system of apprenticeship training and the use of a mobile skilled labour force made it difficult for individuals to protect technical secrets. Since patent laws and patent concessions were commonplace but ineffective, and displayed high barriers to entry, incentives for individually driven innovation were rather weak. Most technical knowledge within industrial regions or districts with integrated skilled labour markets would have been shared, but technological transfer over long distances was inherently rivalrous, because it required non-local patterns of expertise to be applied successfully.

A distinctively European technological system emerged from the late eleventh century, based on craft-based apprenticeship training, non-ascriptive membership of craft associations, and, increasingly, inter-state competition for skilled workers. These three elements defined a set of necessary and sufficient endogenous conditions for the generation, codification and circulation of reliable technical knowledge (Epstein 2005). The craft guild enforced the rules of apprenticeship against free riding and exploitation. Second, it offered institutional, organisational and practical support to the migrant apprentices, journeymen and masters who transferred their technical knowledge from one town and region of Europe to another. Third, it supplied incentives to invention and knowledge sharing that the patent system did not by enforcing temporary property rights over members' innovations. Notably, only the first effect was the outcome of deliberate policy; the other

two were unintended consequences of the club goods that the craft supplied its members. Lastly, and critically, the crafts' jurisdiction was limited in space. Consequently, even the most notoriously restrictive crafts, the glass guild of Venice and the metallurgical guilds of Nuremberg, were unable to stop their members from migrating elsewhere (McCray 1999a; Turner 2006; Lanz 1995: 36).

In the long run, Europe derived its unusual technological momentum from the mobility of its skilled labour. Mobility was the result of three forces.[5] First, there was a great deal of 'ecological' variation in demand across Europe. Second, there were many polities whose rulers' peaceful demand centred on court consumption and somewhat disconnected resources created spatial and temporal variation in demand for skills—thus ensuring a high rate of rotation and a form of technological competition. Third, the same polities were also in persistent and long-term military competition. However, the first factor is not distinctive of Europe, and the second factor would have most probably resulted in a long-term equilibrium. On the other hand, despite its short-term costs, warfare within a system of competing states maintained the economic system in a process of dysequibrium. The periods of most damaging conflict—the late medieval Hundred Years' Wars, the sixteenth-century Wars of Religion, the seventeenth-century Thirty Years War—generated huge shocks to individual regions and drove large numbers of skilled technicians away from their homes. Significantly, these periods of more intense warfare coincided with surges in technical innovation and in the transfer of technological leadership between regions.

Growing state competition and urbanization also reduced the costs of technical dissemination over time. Urbanization offered increased opportunities for exchanging knowledge, higher average quality of labour, a greater likelihood of matching skills to demand, and stronger incentives for the codification of knowledge. Although it is not a priori clear whether high urbanisation attracted skilled migrants, or whether migration (driven by exogenous factors like war) caused high urbanisation, the evidence points to the primacy of the former, pull factors, specifically of urban commercial success. Migration by skilled workers allowed new technological leaders to shift rapidly to the technological frontier, recombine foreign with domestic knowledge, and innovate further. The acceleration of technical innovation during the eighteenth century is more likely to have been caused by increasingly mobile and better-informed technicians sharing both propositional and prescriptive knowledge than by an intellectually driven 'Industrial Enlightenment'.[6]

[5] I owe this formulation to Jean-Laurent Rosenthal.

[6] These conclusions are thus partly at odds with Mokyr's recent argument that the Scientific Revolution and its cultural expression in the 'Industrial Enlightenment' were at the root of the first Industrial Revolution, because they provided the forms of 'propositional' knowledge that technicians lacked (Mokyr 2002). Although I am sceptical about the significance of eighteenth-century natural philosophy for contemporary technical progress, I agree with Mokyr about the importance of information flows for inducing technicians to travel, and possibly—though less testably—to increase their rate of experimentation.

REFERENCES

Acemoglu, D. and J.-S. Pischke (2001). Why do firms train? Theory and evidence. *Quarterly Journal of Economics* (Feb.): 79-119.

Ackermann, J. S. (1977). Introduction. In W. Lotz, *Studies in Italian Renaissance Architecture*. Cambridge, MA-London: The MIT Press, pp.v-xxi.

Addis, W. (1998a). Introduction. In Addis 1998b: xiii-xliii.

Addis, W. (ed.) (1998b). *Structural and Civil Engineering Design*. Aldershot: Aldgate.

Allen, R. C. (1983). Collective invention. *Journal of Economic Behavior and Organization, 4 (1)*, 1-24.

Ash, E. H. (2000). 'A perfect and an absolute work'. Expertise, authority, and the rebuilding of Dover harbour, 1579-1583. *Technology and Culture 41 (2*), 239-68.

Aubin, G. and A. Kunze (1940). *Leinenerzeugung und Leinenabsatz im östlichen Mitteldeutschland zur Zeit der Zunftkäufe*. Stuttgart.

Bairoch, P., J. Batou and P. Chèvre (1988). *La population des villes européennes 800-1850: banque de données et analyse sommaire des résultats*. Geneva: Droz.

Bessen, J. (2005) Patents and the diffusion of technical information. *Economics Letters* 86: 121-28.

Black, A. (1984). *Guilds and Civil Society in European Political Thought from the Twelfth Century to the Present*. London: Methuen.

Blake-Coleman, B. C. (1992). *Copper Wire and Electrical Conductors. The Shaping of a Technology*. Chur: Harwood Academic Publishers.

Bllor, D. (1998). Sociology of knowledge. In E. Craig (ed.) *Routledge Encyclopedia of Philosophy*, London, Routledge.

Brown, J. (1979). *Mathematical Instrument-Makers in the Grocers' Company 1688-1800*. London: Science Museum.

Cahn, W. (1979). *Masterpieces. Chapters on the History of an Idea*. Princeton, NJ.

Calabi, D. and P. Morachiello (2000). Le Pont du Rialto: un chantier public à Venise à la fin du XVIe siècle. In T. Ruddock (ed.), *Masonry Bridges, Viaducts and Aqueducts* (pp. 109-132). Aldershot: Aldgate.

Ceredi, G. (1567). *Tre discorsi sopra il modo d'alzare acque da luoghi diversi*. Parma: Seth Viotti.

Davids, K. A. (1995). Shifts of technological leadership in early modern Europe. In J. Lucassen and K. Davids (eds.) *A Miracle Mirrored. The Dutch Republic In European Perspective*. Cambridge: Cambridge University Press, pp. 338-66.

de Vries, J. and A. van der Woude (1997). *The First Modern Economy. Success, Failure, and Perseverance of the Dutch Economy, 1500-1815*. Cambridge: Cambridge University Press.

Drake, S. (1976). An agricultural economist of the late Renaissance. In Hall and West 1976: 53-73.

Eamon, W. (1994). *Science and the Secrets of Nature. Books of Secrets in Medieval and Early Modern Culture*. Princeton: Princeton University Press.

Epstein, S. R. (1998). Craft guilds, apprenticeship and technological change in preindustrial Europe. *Journal of Economic History, 53 (4)*, 684-713.

Epstein, S. R. (2001). Town and country in Europe, 1300-1800. In S. R. Epstein (ed.) *Town and Country in Europe Between the Fourteenth and the Eighteenth Centuries* (pp.1-29). Cambridge: Cambridge University Press.

Epstein, S. R. (2003). Guilds. In J. Mokyr (ed.) *The Oxford Encyclopedia of Economic History*, Oxford: Oxford University Press.

Epstein, S. R. (2004). Labour mobility, journeyman organisations and markets in skilled labour in europe, 14th-18th centuries. In L.Hilaire-Perez and A.Garçon (eds.), *Pratiques historiques de l'innovation, historicité de l'économie des savoirs (12e – 19e siècles)*. Paris.

Epstein, S. R. (2005). The rise of the West. In J. Hall and R. Schroeder (eds.) *An Anatomy of Power: The Social Theory of Michael Mann*, Cambridge: Cambridge University Press, forthcoming.

Epstein, S. R. and M. Prak (eds.) 2006. *Guilds, innovation, and the European economy, 1400-1800*, London: Routledge, forthcoming.

Ericsson, K. Anders; Krampe, R. Th. and Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100 (3),* 363-406.

Fernie, E. (1990). A beginner's guide to the study of architectural proportions and systems of length. In E. Fernie and P. Crossley (eds.), *Medieval Architecture and Its Intellectual Context. Studies in Honour of Peter Kidson* (pp. 229-238). London-Ronceverte: Hambledon Press.

Frumkin, M. (1947-49). Early history of patents for invention. *Transactions of the Newcomen Society, 26*, 48-56.

Galilei, G. (1638). *Discorsi e dimostrazioni matematiche intorno a due nuove scienze attenenti alla mecanica et i movimenti locali*. Leiden: Elsevier.

Grafton, A. (2000). *Leon Battista Alberti. Master Builder of the Italian Renaissance*. Cambridge, MA: Harvard University Press.

Griffiths, T., P. A. Hunt, and P. K. O'Brien (1992). Inventive activity in the British textile industry, 1700-1800. *Journal of Economic History* 52 (4), 881-906.

Hall, B.S. and D. C. West (eds.) (1976). *On Pre-Modern Technology and Science. A Volume of Studies in Honor of Lynn Whyte, jr.* Malibu: Undena Publications.

Hamilton, S. B. (1998). The place of Sir Christopher Wren in the history of structural engineering. In Addis 1998b: 193-208.

Harris, J. R. (1978). Attempts to transfer English steel techniques to France in the eighteenth century. In S. Marriner (ed.), *Business and businessmen: studies in business, economic and accounting history*. Liverpool: Liverpool University Press.

Harris, J. R. (1992). *Essays in industry and technology in the eighteenth century: England and France*. Hampshire/Brookfield: Ashgate.

Harris, J. R. (1998). *Industrial espionage and technology transfer. Britain and France in the eighteenth century*. Aldershot: Ashgate.

Hilaire-Pérez, L. (1991). Invention and the state in eighteenth-century France. *Technology and Culture* 32(4): 911-31.

Hilaire-Pérez, L. (2006). Inventing in a world of guilds: the case of silk fabrics in Lyon in the eighteenth century, in Epstein and Prak 2006.

Hollister-Short, G. (1976). Leads and lags in late seventeenth-century English technology. *History of Technology, 1*, 159-183.

Hollister-Short, G. (1995). Invisible technology, invisible numbers. *ICON, 1*, 132-147.

Kubler, G. (1982). *Building the Escorial*. Princeton: Princeton University Press.

Lanz, H.-P. (1995). Training and workshop practice in Zürich in the seventeenth century, in Mitchell (1995), pp.32-42.

Lefèvre, W. (2003). The limits of pictures: cognitive functions of images in practical mechanics - 1400 to 1600. In Lefèvre, Renn and Schoepflin 2003: 69-89. *power of images in early modern science*

Lefèvre, W., J. Renn and U. Schoepflin (eds.) (2003). *The* (pp. 69-89). Basel/Boston/Berlin: Birkhäuser

MacLeod, C. (1987). Accident or design? George Ravenscroft's patent and the introduction of lead-crystal glass. *Technology and Culture, 28*(4), 776-803.

MacLeod, C. (1988). *Inventing the Industrial Revolution. The English Patent System, 1660-1800*. Cambridge: Cambridge University Press.

Machlup, F. and E. Penrose (1950). The patent controversy in the nineteenth century. *Journal of Economic History* 10 (1): 1-29.

Mainstone, R. J. (1968). Structural theory and design before 1742. *Architectural Review, 143*(April), 303-310.

Mainstone, R. J. (1998). Stability concepts from the Renaissance to today. In Addis 1998b: 171-192.

Mark, R. (1978). Structural experimentation in Gothic architecture. *American Scientist, 6*, 542-550.

Martini, F. di G. (1967). *Trattati di architettura ingegneria e arte militare* (Maltese, Corrado ed.). Milan: Il Polifilo.

McCray, W. P. (1999). *Glassmaking in Renaissance Venice. The fragile craft*. Aldershot-Brookfield, Aldershot.

McCray, W. P. (1999). Creating networks of skill: technology transfer and the glass industry in Venice. *Journal of European Economic History* 28 (2): 301-334.

McGee, D. (2003). Ships, science and the three traditions of early modern design. In Lefèvre, Renn and Schoepflin 2003: 28-46.

Merges, R.P. (2004). *From medieval guilds to open source software: informal norms, appropriability institutions, and innovation*. Paper presented at the annual Economic History Association Conference, San Diego, September.

Mitchell, D. ed. (1995) *Goldsmiths, silversmiths and bankers: innovation and the transfer of skill, 1550 to 1750*. Stroud / London: Alan Sutton / Centre for Metropolitan History.

Mokyr, J. (2002). *The Gifts of Athena. Historical Origins of the Knowledge Economy.* Princeton/Oxford.

Molà, L. (2004). Il mercato delle innovazioni nell'Italia del Rinascimento. In M. Arnoux and P. Monnet (eds.) *Le tecnicien dans la cité en Europe occidentale, 1250-1650*. Rome: École française de Rome, pp.215-250.

Neal, L. (2000). How it all began: the monetary and financial architecture of Europe from 1648 to 1815. *Financial History Review* (7) 2, 117-140.

Newman, W. R. (1998). Alchemical and Baconian views on the art/nature division. In A. G. Debus and M. T. Walton (eds.), *Reading the book of nature. The other side of the Scientific Revolution*. Kirksville, MI: Truman State University, pp.81-90.

Newman, W. R. (1999). Alchemical symbolism and concealment: the chemical house of Libavius. In P. Galison and E. Thomson (eds.), *The architecture of science*. Cambridge, MA-London: The MIT Press, pp.59-77.

Newman, W. R. (2000). Alchemy, assaying, and experiment. In F. L. Holmes and T. H. Levere (eds.), *Instruments and experimentation in the history of chemistry*. Cambridge, MA/London: MIT Press, pp.35-54.

North, D. C. (1981) *Structure and change in economic history*. New York: W.W. Norton.

Palissy, B. (1996). *Oeuvres complètes* (M.-M. Fragonard ed.). Mont-de-Marsan: Editions InterUniversitaires.

Persson, K.G. (1999). *Grain markets in Europe, 1500-1900. Integration and deregulation*. Cambridge: Cambridge University Press.

Pfister, U. (2006). Craft guilds and technological change. The engine loom in the European silk ribbon industry in the seventeenth and eighteenth centuries, in Epstein and Prak (2006).

Popplow, M. (2002). Models of machines: a 'missing link' between early modern engineering and mechanics? *Max-Planck Institut für Wissenschaftsgeschichte Preprints, 225*.

Prak, M. (2006). Guilds and the development of the art market during the Dutch Golden Age, in Epstein and Prak (2006).

Raven, D. (2005). Craft knowledge is knowledge enough. Mimeo, Department of Anthropology, Utrecht University.

Reber, A. S. (1993). *Implicit learning and tacit knowledge. An essay on the cognitive unconscious*. Oxford-New York: Oxford University Press.

Roche, D. (2003). *Humeurs vagabondes. De la circulation des hommes et de l'utilité des voyages*. Paris, Fayard.

Rosenband, L. N. (2000). *Papermaking in eighteenth-century France. Management, labor, and revolution at the Montgolfier mill 1761-1805*. Baltimore-London: The Johns Hopkins University Press.

Sanabria, S. L. (1998). The mechanization of design in the 16th century: the structural formulae of Rodrigo Gil de Hontañon. In Addis 1998b: 1-14.

Sandman, A. D. (2001). *Cosmographers vs. pilots: Navigation, cosmography, and the state in early modern Spain.* Unpublished Ph.D., University of Wisconsin-Madison, Madison.

Schilling, H. (1983). Innovation through migration: the settlements of Calvinistic Netherlanders in sixteenth- and seventeenth-century Central and Western Europe. *Histoire Sociale/Social History* 16 (31): 7-33.

Scoville, W. C. (1953). Minority migrations and the diffusion of technology. *Journal of Economic History 11 (3)*, 347-360.

Shapin, S. (1988). The house of experiment in seventeenth-century England. *Isis, 79*, 373-404.

Shelby, L. R. (1976). The 'secret' of the medieval masons. In Hall and West 1976: 201-222.

Smith, C. S. (1956). Introduction. In A. Grünhaldt Sisco (ed.), *Réamur's Memoirs on steel and iron. A translation from the original printed in 1722.* Chicago: University of Chicago Press, pp. vii-xxxiv.

Trogu Rohrich, L. (1999). *Le tecniche di costruzione nei trattati di architettura*. Monfalcone (Gorizia): Edicom.

Trudaine de Montigny, A. (1752) Projet tendant à perfectionner les fabriques de France, in P. Boissonnade 190*. Trois mémoires relatifs à l'amélioration des manufactures de France sous l'administration des Trudaine (1754). *Revue d'histoire économique et sociale* **: 56-85.

Turner, A. (2006). 'Not to hurt of trade'. Guilds and innovation in horology and precision instrument-making, in Eptein and Prak 2006.

Unger, R. W. (1978). *Dutch Shipbuilding before 1800. Ships and Guilds*. Assen-Amsterdam: Van Gorcum.

von Simson, O. G. (1998). The Gothic cathedral: design and meaning. In Addis 1998b: 159-170.

von Stromer, W. (1978). *Die Gründung der Baumwollindustrie in Mitteleuropa. Wirtschaftspolitik im Spätmittelalter*. Stuttgart.

Wildasin, D. E. (2000). Labor-market integration, investment in risky human capital, and fiscal competition. *American Economic Review, 90*(1), 73-95.