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TECHNOLOGICAL CHANGE AND THE ECONOMIC EXPANSION OF THE DUTCH REPUBLIC, 1580-1680*

by

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1. Introduction

Expert observers in the past and eminent historians today are agreed that the Dutch Republic displayed a remarkable level of technological skill. `The people of the United Provinces', Cardinal Guido Bentivoglio declared in 1611, `are very proficient in all the arts, but especially the manual and mechanical ones'[1]. Samuel Buschenfelt, who in the early 1690s by order of the Board of Mines in Stockholm made a long voyage in western Europe to get acquainted with every piece of technology that could possibly be of use to the Swedish state, thought Holland could rightly be called an `officina machinarum'[2]. Thomas Nugent stated in his *Grand Tour*, published in 1749, that `there [was] no nation where the people apply themselves with more diligence to all manner of mechanic arts, than the inhabitants of the United Provinces'[3]. Abbé Rozier, member of the Académie Royale des Sciences, was equally impressed by the achievements of the Dutch. `Le besoin et l'amour du gain ont porté d'un tel degré de perfection toutes les machines', he reported in 1777 after visiting Holland in the company of his fellow-Académicien Desmarest, `qu'on est en droit de dire que les roues de nos montres ne marchent pas avec plus d'exactitude'[4].

Among economic historians, the late Charles Wilson was the first to recall attention to `technological prowess' as a key factor in the growing prosperity of the Dutch Republic[5]. Jan de Vries remarked that the Republic `owed much of its rise as an industrial power to a series of technological advances'[6]. And Jonathan Israel, too, has stated that the pre-eminence of the Dutch in industrial production in the seventeenth century was essentially based on its technological superiority[7].

The evolution of technology in the Dutch Republic has given rise in the past century to a substantial body of scholarship. While the topic is nowadays no longer as widely studied by economic historians as it used to be up to the 1950s, it still constitutes a lively field of research for specialists from various other streams of historical inquiry[8].

Taking this long and varied tradition of scholarship as a starting point, this essay will first attempt to assess the contribution of technological innovations to the economic expansion of the Northern Netherlands between around 1580 and the end of the seventeenth century. What did the expansion owe to technological advances? Discussion of this issue leads us naturally to consider more closely the actual pattern of technological change that occurred in the Dutch Republic. These matters are the subject of the first two sections of this article. In the third and final section, the essay will explore how best to explain why certain technological innovations emerged and were selected, and not others.

2. Technological change and social savings

Modern economic scholarship shows that it is extremely hard to pin down the role of technological change in economic growth. Even if economists are generally agreed that growth of production cannot fully be explained by enhanced inputs of capital and/or labour alone, it is by no means easy to determine to what extent the residual may be ascribed to advances in technology. Statements about the contribution of technological innovations remain at best approximations, and this is all the more true for the early modern period, for which data are often defective or even completely lacking. Any attempt to quantify the role of technological change in the expansion of the Dutch Republic is thus bound to produce only very crude results.

Keeping these limitations in mind, the task at hand may be tackled from two sides: either one takes a given innovation as starting point and then attempts to assess its overall impact on the economy, or one starts from known sectors of growth and then tries to identify changes in technology that preceded or accompanied the growth in these particular sectors.

The first approach was employed some years ago in studies on changes in energy use and inland navigation in the Netherlands between the sixteenth and nineteenth centuries. The guiding concept in these cases, borrowed from

earlier research on nineteenth-century economic history in Britain and America, was `social savings'. According to this approach, the importance of an innovation in a given sector may be assessed by estimating the amounts of resources that would have had to be reallocated to that sector if the innovation had in fact not been put into practice or, in other words, the amounts that had been saved by its application.

The most far-reaching claims on the basis of such calculations are those made by J.W. de Zeeuw in a ground-breaking study on the availability of energy[9]. De Zeeuw argued that the prosperity of the Dutch Republic in the Golden Age was to a large extent due to the immense savings in land and labour made possible by the easy accessibility of peat. Peat deposits were not unique to the United Provinces. But the stark fact was that the efforts required to exploit them were much smaller than anywhere else. Peat deposits in the Netherlands could easily be reached by digging navigation canals into peat areas and linking these up with existing networks of natural waterways. Thanks to the highly developed system of inland navigation, all major cities in the country were assured a regular supply of cheap fuel. The annual consumption of peat in the seventeenth century, according to De Zeeuw's calculations, amounted to over 6,000 thousand million kcal, or around 4 million kcal per capita[10]. The amount of energy derived from other sources pales in comparison. Windmills used in industry provided no more than 45 thousand million kcal per year, and the energy supplied by wind power in inland navigation amounted to a mere 36 thousand million. The contribution from wood and coal was even less[11].

The easy availability of peat, De Zeeuw asserted, had profound consequences for the development of the Dutch Republic. The abundance of cheap fuel lay at the root of the growth of a whole array of fuel-intensive industries. Owing to the cheap energy supplied by peat, the Northern Netherlands developed into a leading centre of production in such industries as brewing, distilling, brick and tile making, ceramics, bleaching, textile dyeing, salt boiling and sugar refining. The large-scale exploitation and burning of peat, together with the use of wind power in inland navigation and industrial windmills, resulted in immense savings in land and labour. If the Dutch economy in the seventeenth century had had to do without the heating energy derived from peat and the mobile or stationary motion energy provided by wind power, and had instead (like most other countries in Europe) largely relied on the use of firewood, horses and human labour to obtain the same quantity of energy, it would have needed an additional labour input of at least 165,000 man-years per year and an extra acreage of almost three million hectares to feed the horses and supply the timber. The exceptional system of energy production in the Dutch Republic, De Zeeuw concluded, liberated vast resources for other sectors of the economy. The Golden Age was `born of peat'[12].

Another advance in inland navigation generated even further social savings, Jan de Vries has argued. The system of passenger transportation by towed barges (*trekschuiten)* along a separate network of canals (*trekvaarten*) developed in the maritime provinces of the Republic between 1632 and 1667 led to a significant decrease in costs compared with the prevailing alternative mode of transportation, the horse-drawn coach. Net benefits to the economy by the reduced input of horsepower were estimated by De Vries at around 0.8% of the gross regional product (GRP) in the period 1665/1675; compared with sailing vessels costs outweighed benefits by a narrow margin. The GRP was calculated by multiplying an estimated income per capita (borrowed from Gregory King) by the conjectured number of households living in the maritime area served by the *trekvaart* system. In terms of the consumers' surplus (the benefits in money or time as valued by the passengers) the social savings were assessed at around 0.2% of the GRP compared with transportation by sailing vessels and 0.5% if the horse-drawn coach was taken as the most likely alternative[13]. De Vries concluded that the *trekvaart* network was `no marginal feature' of the Dutch economy. For a preindustrial innovation, its impact could be called `remarkable'[14].

What do the estimates presented by De Zeeuw and De Vries tell us about the actual importance of the advances in energy production and inland transportation? De Vries's cautious conclusion about the relative contribution of the *trekschuiten* system hinges, of course ? as he was at pains to point out ? on the absolute size of the gross regional product. If King's estimate of the per capita income in the Dutch Republic is far off the mark, the reliability of the conclusion decreases accordingly. If income in the Republic in the late seventeenth century was twice as high as King assumed ? and this is what De Vries argued in a later paper[15] ? then the actual contribution of the *trekschuiten* system to economic growth by 1665/1675 was of course far less than the figures suggest. Even so, De Vries has made a good case for concluding that the introduction of this system must have implied at least *some* social savings vis-à-vis the predominant alternative mode of transportation.

The results obtained by De Zeeuw have been seriously challenged by R.W. Unger[16]. First of all, Unger showed that De Zeeuw overestimated the annual consumption of thermal heat derived from peat by a very wide margin. He arrived at a figure that was only a fifth as large as De Zeeuw's[17]. Second, Unger argued that probably half of the energy embodied in peat was lost to effective work due to the use of inferior ovens, and moreover, that presumably more than 50% of all peat was used for home heating rather than for industrial production. Thus the contribution of peat to the advance of industry (and, by implication, to economic growth) may have been far less than De Zeeuw's

figures suggest[18]. Third, De Zeeuw is said to have erred in the other direction by underrating or neglecting the role of other energy sources. Wind power turns out to have been far more important than De Zeeuw allowed, if one takes into account the amount of energy supplied by wind in international shipping ? a sector that De Zeeuw completely left out of consideration[19]. The contribution from coal, which De Zeeuw dismissed out of hand, was in reality far from slight. It became ever more significant as time went by, and particularly so in industrial production. Between the middle of the sixteenth century and the end of the eighteenth century in Holland, one branch of industry after another shifted from peat to coal as its principal source of fuel: brewing, distilling, sugar refining, soap boiling, bleaching and copper working. The total energy supplied by coal increased from one-third as much of that derived from peat by the late seventeenth century to more than twice as much a hundred years later. And in contrast with peat, coal was used almost exclusively in industrial production, and not to heat homes[20].

One can take the criticism even further on two points. The argument on input of energy sources unfolded by De Zeeuw nowhere allows for the contribution of yet another source of energy: water power. Water-powered mills could in fact be found in many parts of the inland regions of the Dutch Republic and ? in the form of tide mills ? even in Holland and Zeeland. They provided energy for a wide variety of purposes, including corn grinding, oil pressing, paper making, copper working, bark milling and fulling. The total number of water-powered mills is not known exactly, but it must have run into several hundreds by 1700. The number of paper mills on the Veluwe alone amounted to 170 in the early eighteenth century[21], and by then there must have been dozens of other mills in operation along the rivers, brooks and creeks of Gelderland, Twenthe, Brabant, Limburg and Utrecht. Some twenty tide mills were still in action at that time in Holland and Zeeland[22].

The importance of wind power for economic growth in the Netherlands is even more understated in De Zeeuw's estimate than Unger has demonstrated, due to his cursory treatment of the role of wind-driven drainage mills. De Zeeuw left them out of consideration with the argument that they made no net contribution to the national energy supply. His inferences with regard to the role of peat and wind power in inland transportation, however, went much beyond their supposed contribution to the energy supply of the Dutch Republic. He even asserted that savings in land and labour realized by the large-scale use of peat, together with the extensive system of inland navigation, lay at the very base of the whole economic and cultural upsurge of the Netherlands in the Golden Age.

But if one is willing to press the case that far, it seems fit, for the sake of consistency, to consider the savings in land and labour achieved by the spread of drainage mills in the maritime provinces beginning in the fifteenth century. Given the prolonged subsidence of the soil since the Late Middle Ages, it would be hard to overestimate the importance of drainage mills. If it had not been for these wind-driven *poldermolens,* either most of the land in Holland would have become progressively unfit for human habitation and agricultural use, or the resources in land and labour saved by the employment of peat would have largely been spent to operate increased numbers of human or animal-driven mills just to keep the land tolerably dry[23] (according to De Zeeuw's own estimate, the use of 3,000 windmills in industry saved the input of approximately 300,000 people or 50,000 horses[24]). In either case, the savings generated by the use of peat can surely not be rated higher than those realized by that familiar national symbol, the windmill.

The social savings approach has as yet not been applied to other fields of technology than energy use or inland transportation. The reason may well reside in the limitations which will have become obvious from the preceding discussion. Even if the comparison between a real and a hypothetical situation is accepted in theory as a valid one, it is extremely hard to put the method into practice without making assumptions that largely deprive the comparison of its usefulness. In many cases it may turn out to be almost impossible to identify any alternative technology with which the impact of a given new technology may be meaningfully compared. For example, how could one ever calculate the social savings effected by the introduction of the manufacture of tobacco pipes?

3. Productivity change and technological innovation

The second method for examining the role of technological innovation in economic growth consists in taking as starting point a sector of the economy that is known to have contributed substantially to the general expansion, and then seeking to identify specific changes in technology that preceded or accompanied growth in that particular sector. Needless to say, such an analysis cannot be applied in the early modern Netherlands as rigorously as one would wish. There is as yet insufficient evidence to permit a complete assessment of the role of output or productivity growth in every sector of the economy, or to determine the weight of each sector in the economy as a whole. The figures that have been produced are at best informed guesses. It will, moreover, be hard, if not virtually impossible, to isolate changes in technology from changes in the organization of production. One will often have to settle for the bare observation that a rise in output or productivity was indeed preceded or accompanied by specific advances in techniques, without being able to tell for sure to what extent the latter really influenced the former.

Be that as it may, a few basic facts concerning economic growth in the early modern period (as presented in the contribution by Van Zanden) will hardly be contested: 1) that growth in the Northern Netherlands after 1580 was on average more rapid than before, (2) that it comprised a very broad range of sectors, (3) that annual rates of expansion in industry and international services were higher than those in agriculture or deep-sea fisheries (with the likely exception of whaling); and (4) that gains in output in new or restructured branches of industry like paper making or textile manufacturing generally surpassed those in established industries like brewing or soap boiling. Assuming for the moment that these general assessments are essentially correct, the main task of this section will be to explore whether the observed growth in various sectors of the economy was indeed preceded or accompanied by specific changes in technology.

It may be helpful to adopt a distinction that was previously used by H. van der Wee to describe the general shifts in industrial structure occurring in the Low Countries between the Late Middle Ages and the end of the eighteenth century, and that was in a sense used by Israel in his study on the Dutch Republic as well. This concerns the essence of growth: productivity increase. Aside from a group of industries whose strength resided in introducing improvements leading to a rise in the *physical* productivity of labour ? i.e. an increase in the number of items produced per manhour input ? Van der Wee distinguished another group whose growth was due mainly to the enhanced input of highly skilled labour leading to a *qualitative* surplus value per item produced. In the latter case, economic productivity may still increase, even if productivity in a physical sense is stagnant or declines [25].

If slightly modified, this particular distinction, I submit, can also usefully be applied to understand how technological development contributed to the expansion of the Dutch Republic. The rise in productivity did not occur only in industry, but in other sectors of the economy as well; it did not necessarily result entirely from changes in organization but could also stem from developments in technology; and, finally, it could involve more factors of production than labour alone.

Herring fishing and whaling

Herring fisheries are the prime example of a sector that saw a decrease in rate of growth of production beginning in the late sixteenth century; after the middle of the next century, the industry was by all accounts in absolute decline[26]. The rise in output which continued up to around 1650 was due to changes in organization and technology that largely dated from the first decades of the fifteenth century: increased concentration of capital and marketing, development of extensive arrangements for quality control by means of close cooperation between producers, introduction of a type of vessel especially suited for use in deep-sea fishing (the herring buss) and continual refinement of the technique of curing herring aboard ship[27].

Although it remains a moot point whether the last-named development led to a substantial rise in the physical productivity of labour in herring fishing ? as savings through reducing time spent in port may well have been offset by the increased need for labour to repack the herring once the buss had delivered the catch on land ? there is no doubt that it resulted in long-term advance in economic productivity thanks to the continued enhancement of quality. Indeed, the quality of pickled herring from Holland improved to such an extent that by the late sixteenth century it was far superior to any of its rivals. Dutch herring fetched higher prices than herring marketed from England, Scandinavia or France[28]. The elaborate institutional arrangements for the fishing industry which developed in the early modern period largely served to secure this established lead in quality and the enhanced level of prices that went with it, even to the extent of ultimately reducing the volume of production[29].

Developments in whaling were exactly the opposite of those in herring fishing. Whale oil was generally held to be of lower quality than vegetable oil long before the start of Dutch whaling around 1610. This became all the more true when the practice of boiling the blubber on the spot at Spitsbergen was gradually abandoned in the middle decades of the century in favour of processing the whole catch in Holland. Once the charter of the Noordse Compagnie, which monopolized whaling from the Netherlands from 1614, had expired in 1642, total production in terms of the number of whales caught expanded rapidly from some 150 per year to a level of 500 to 1500. The few technological changes introduced between 1610 and 1670, such as the improvement of harpoons or the doubling of the hull of the whaling ship, were aimed at increasing physical productivity or preventing loss of capital rather than enhancing quality. Efforts to raise the total value of the catch by devising new uses for the by-product, whale-bones, remained largely unsuccessful until changes in fashion in the last decades of the seventeenth century eventually led to a sudden rise in demand[30].

Agriculture

Growth in agriculture, which started long before the Dutch Republic came into being, presumably reached its peak in

the period between 1580 and 1650. Output and productivity appear to have risen more rapidly than before. Both De Vries and Van Zanden have estimated that the productivity of the land in the coastal provinces between the 1570s and the middle of the seventeenth century increased by some 50%[31]. The evidence collected by De Vries strongly suggests that the expansion stemmed both from changes in the organization of production ? viz. increased specialization among rural households ? and from changes in technology.

Output per farm improved due to a variety of innovations such as regular manuring, crop rotation, better breeding practices, improved feeding methods and the development of more advanced drainage techniques[32]. Drainage windmills spread throughout the maritime provinces of the Northern Netherlands after the early fifteenth century[33]. In the eastern part of Delfland (near Delft), for instance, the number of *poldermolens* rose from six around 1440 to fourteen in 1483 to eighteen in 1552[34]. In the district of Schager Koggen and Niedorper Koggen in the northern part of Holland their number increased from just one in 1467 to five in 1514, fourteen in 1544, seventeen in 1584 and twenty-two in 1653[35]. Improvement of drainage further involved building dikes, sluices and reservoirs and introducing detailed rules for regulating the water level. The net result of this whole set of technological advances was both a rise in the quality of the soil and a more productive stock of cattle. The diffusion of new mechanical devices that permitted significant savings in labour, such as winnowing mills, horse- (or dog-) powered churn mills or horse-drawn threshing blocks appears not to have started until after the middle of the seventeenth century[36].

The tendency to improve economic productivity by concentrating on the production of high-quality goods was less pronounced in the agricultural sector than in the herring fisheries. There were pockets of `luxury' producers, to be sure, like bulb growers near Haarlem or tree cultivators in the neighbourhood of Boskoop[37]. But tobacco cultivation in Utrecht and Gelderland flourished rather by moving to the opposite side of the sprectrum, viz. by supplying cheaper produce than the fine tobacco imported from America[38]. And the madder producers on the islands of Zeeland and South Holland, who boasted a tradition of quality control that went back to the middle of the fourteenth century, always took pains to cater to more than one section of the market. The hallmark of madder growers in the Netherlands up to the nineteenth century was precisely their ability to deliver their produce in every variety and quality that might be demanded. All the while the technology employed remained essentially unchanged[39].

Merchant shipping

By all accounts, the shipping industry of the Northern Netherlands expanded extremely rapidly both before and after the Dutch Revolt, though the rate of growth in the size of the merchant fleet may have slowed down somewhat after the 1580s. As in agriculture, the expansion rested, at least in part, on a rise in physical productivity. According to the well-known study by Violet Barbour, by the 1620s labour productivity in Dutch merchant shipping was the envy of foreigners. The ratio of tonnage served per man on Dutch vessels was said to be at least thrice as high as on English ones. The shipping industry in England managed to raise its own productivity later in the century precisely by adopting various features of ship design that had earlier been developed in the Dutch Republic[40]. Meanwhile, from the 1630s onwards, productivity in the Dutch merchant fleet increased still further. In every branch of shipping, the ratio of tonnage per man on Dutch merchantmen around 1700 was half as much again as seventy years before[41].

These sustained gains in productivity were undoubtedly partly achieved by advances in technology. During the sixteenth century, and especially after 1550, Dutch shipbuilding saw an extremely swift and broad proliferation of ever more efficient designs, which in the 1590s culminated in the introduction of the efficient ship par excellence, the *fluyt*[42]. It was first and foremost the diffusion of this specific type of ship that permitted the vast increase in labour productivity in the Dutch merchant marine in the early seventeenth century (and later in the English merchant navy as well). While the rate of change in designs of sea-going vessels slowed down noticeably after 1630, improvements in rigging continued throughout the seventeenth and eighteenth centuries[43]. These ongoing changes in technology, together with a more efficient organization of work aboard ship[44], may to some extent explain the rise in productivity of labour between 1630 and 1700.

The productivity gains by improvements in ship design were consolidated and probably even extended by changes in other domains of technology that were of crucial importance to the shipping industry. First, the benefits of the newly introduced types of ship in the ocean trades could only be reaped to the full thanks to the rapid advances in navigation techniques that facilitated the expansion of Dutch ocean shipping starting in the late sixteenth century[45]. Second, the construction of new harbour facilities and the introduction of new dredging equipment and other devices to ease the safe passage of ever larger ships in all probability reduced loss of time in ports and on access routes to ports.

J.P. Sigmond identified a total of 38 harbour extension schemes carried out in sixteen different ports in Holland, Zeeland and Friesland between 1570 and 1650, as against only seven (in three cities) during the seven preceding

decades and just five (in as many towns) in the following 150 years. In many port towns that participated in international shipping, the total harbour area grew twice or even three times as large. The growth in capacity usually accompanied an increased separation of domains inside the port area between the main branches of shipping ? merchant marine, fishing industry, Navy and East India Company ? and an extended supply of such vital facilities as cranes, sheers, lighters, repair yards and buoyage and pilotage services[46]. In order to stave off the perennial threat of silting, every port city of any importance made continual efforts to remove the amassed mud from its harbour by means of dredge-nets, scrawlers or mud-mills. The town of Amsterdam, which around 1590 was the first to adopt a mud-mill with a rotating chain of scoops, had two large and two small copies of this engine in operation by 1677. The capacity of the mills substantially increased after 1620, when human labour was replaced by horsepower[47].

Industry

Among all sectors of the economy it was probably industry that saw the highest rates of growth after 1580. But industry by no means presents a picture of unmitigated technological advance. The relationship between expansion of industry and change in techniques was in fact somewhat uneven. Among the three branches that traditionally constituted the core of the industrial sector in the Northern Netherlands and continued, or recommenced, to grow after the late sixteenth century ? brewing, shipbuilding and textile manufacture ? each showed a quite different rate and pattern of technological evolution.

The beer industry did not see any marked change in the process of brewing itself. There was no improvement in quality that could even remotely be compared to the spread of hopped brewing in the fourteenth century. The few innovations that occurred largely involved input of energy and supply of raw materials. Between 1560 and 1650, breweries increasingly changed over from peat to coal, and some of them perhaps attempted to reduce production costs by adopting fuel-saving devices[48]. It is striking that among the more than twenty fuel-saving inventions known to have been proposed in the Netherlands between 1500 and 1650, all but three were certainly intended for use in breweries[49]. In order to ensure a continual supply of fresh water in wintertime ? and thus prevent any stoppage in production ? ten brewers in Amsterdam in 1651 decided to jointly invest in an ice-breaker to keep open the canals from nearby Weesp, where they fetched their water[50]. A new device for that purpose had been patented as early as 1633 by an inventor from another beer-producing town, Elias Christiaensz. of Haarlem[51]. The ice-breaking enterprise remained in business for over 130 years.

In shipbuilding, increased productivity after 1600 was in all probability due both to ongoing changes in organization and to developments in production techniques. The tendency towards centralization of production with a small number of firms, which was already in evidence in established centres of shipbuilding like Haarlem by 1600[52], became even stronger in the district that came to dominate the industry after 1630, the Zaanstreek. Production time per ship was reduced by standardized design, more rigorous organization of work, increased division of labour, and large-scale adoption of capital equipment that had first been introduced on wharves in the late sixteenth century, such as cranes, jackdaws and slipways. Construction costs were further kept down by the easy and relatively low-cost supply of sawed wood, thanks to the huge expansion of timber sawing in the Zaanstreek since the introduction of the wind-powered sawmill in the 1590s. The number of sawmills along the Zaan rose from 53 in 1630 to 256 by 1731[53].

Just like shipbuilding, textile manufacturing owed its renewed expansion after the 1580s partly to the employment of mechanical devices that enhanced the physical productivity of labour. Fulling mills, which had been introduced in Holland from Flanders and Brabant about the middle of the sixteenth century[54], spread to all major cloth-producing towns, and to the Zaanstreek, between 1585 and 1640. Leiden had 25 of them by 1650. Most of these were horse-powered mills or windmills[55]. Twining mills expanded both in absolute numbers and productive capacity up to the middle of the century. Thanks to the introduction of an advanced type of hot press, the time required for the pressing of serges (in the finishing stage of the manufacturing process) was reduced from six hours in the 1580s to just one hour in the 1630s[56]. Ribbon weaving was revolutionized by the appearance of the ribbon frame, patented in 1604, which permitted a single worker to weave twelve ribbons at a time (and by 1670 even twice as much). It was widely adopted in all the main textile centres of Holland by the late 1660s[57].

But the principal thrust of technological development in textile manufacturing aimed at bettering the *quality* of production. The development can be roughly divided into two phases. In the first one, lasting from c.1590 till the 1630s, the value of the fabrics produced was enhanced by improvements in the finishing stage. These improvements mainly involved the employment of new materials, or new combinations of materials, in dyeing operations (for instance indigo, cochenille, potash and tartar) and the large-scale use of human- or animal-powered machinery like calender-mills and polishing mills to give a shinier appearance to the end-products[58]. While improvements of this

type continued after the 1630s, the emphasis in technological evolution from the second quarter of the seventeenth century onwards shifted more and more towards the increased use of high-grade raw materials such as merino wool from Spain, mohair yarn from Turkey and raw silk from China, Persia and later Bengal[59]. The lead of the Dutch Republic in textile manufacturing in the last decades of the century rested, as far as technology was concerned, primarily upon the employment of first-rate raw materials.

What happened in textile manufacturing also occurred in many other expanding industries in the Dutch Republic between 1580 and 1680, both the established ones and the newly founded. The vital technological knowledge that preceded or accompanied growth was, in its initial stages, generally adopted from abroad, but relied increasingly on home-grown innovations as time went on. In many sectors, technology began to be imported even before the outbreak of the Dutch Revolt. Such advances commonly comprised more than just the introduction of methods or machines that permitted a steady rise in physical productivity. They also consisted in the improvement of quality through the growth of skills and the input of new raw materials, or new mixtures of these. And the latter route became ever more important after the second quarter of the seventeenth century.

There were exceptions, of course. The brick industry, for instance, which had grown into a major rural industry long before the 1580s, saw no significant advances in technology during its continued expansion in the seventeenth century. Among the few changes to be observed, the most important were perhaps the invention of new varieties of brick and the use of a horse-powered mill for cleaning clay. Buschenfelt examined a copy of this mill in the 1690s[60]. Sugar refining in the Dutch Republic, which was first established by immigrants from the Southern Netherlands in the 1590s, was similarly unmarked by technological innovation during its recurrent phases of expansion, until the very end of the seventeenth century when many producers began to substitute oxblood for eggs as an agent in the refining process[61]. But evolution in other growth industries commonly conformed to the pattern sketched above.

Earthenware production in Delft, for example, grew into a leading export industry by the middle of the seventeenth century after a number of entrepreneurs in majolica production (which owed its rise after 1560 largely to the immigration of skilled workmen from the Southern Netherlands) from 1620 onwards ventured into the manufacture of faience in imitation of porcelain imported from China. This successful shift towards a higher segment of the market was partly accomplished by a series of changes in technology: the large-scale input of marl from England and Tournay, the development of new methods for mixing this novel ingredient with inland clay, the introduction of new techniques and implements for glazing and baking, and finally, the improvement of skills in decoration[62]. Tobacco-pipe manufacture, introduced in the Dutch Republic by immigrants from England about 1610, saw a continuing evolution in design as well as in glazing and baking techniques in the middle decades of the century due to efforts of native craftsmen. As a result, by the 1680s the industry furnished the market with clay pipes of every quality imaginable, from luxury types down to the most ordinary models[63]. In another expanding branch of industry that owed its existence to foreign workmen and entrepreneurs, the processing of tobacco, technological advances achieved by Dutch craftsmen from 1630 onwards involved not only an increase in the physical productivity of labour through the application of mechanical devices like wheels, presses and spindles, but also the production of special sauces which improved flavour, flammability and storage life[64]. Innovations introduced by Dutchmen in the manufacture of white lead in the early seventeenth century (which probably started about 1600 on the initiative of immigrants from the Southern Netherlands) likewise involved more than just a minor rise in physical productivity. It led to such an improvement in quality that white lead from Holland ranked first well into the nineteenth century[65]. All the industries mentioned in this paragraph show the pattern of the main improvements being in quality rather than quantity.

Technological change in such growth industries as timber sawing, oil pressing or paper making did not simply consist in the large-scale application of wind power to production techniques that were adopted unaltered from abroad. In the course of the seventeenth century, in every case, the introduction of wind power (which ensured high production per manhour) was accompanied by additional changes in machinery and by improvements in other parts of the production processes such that the quality of the end-product, too, was higher than could be attained by traditional techniques. Windmills in the Zaanstreek could deliver wood more finely sawn, oil better pressed and paper made more perfect than any other production centre in Europe at the time[66].

Thus the pattern of technological change in the Dutch Republic between c.1580 and 1680 was in fact more complex than it may appear at first sight. For one thing, change could mean enhancement of the physical productivity of labour. For another, it could mean an increase in quality per item produced. And often the two ways were to some extent combined.

4. Explaining technological change in the Dutch Republic

Selection of novelties

How can the striking technological advance in the Dutch Republic be explained? In recent years several authors have hypothesized that the prime determinants of change must have been relative factor prices. Jonathan Israel maintained that investment in technological innovation was largely induced by a combination of high wages and low interest rates[67]. Jan de Vries suggested that the high level of wages in the Dutch Republic induced a strong bias towards the introduction of labour-saving techniques, viz. the application of techniques that involved a more intensive use of capital or of non-human energy sources like peat or windmills[68].

The evolution of the prices of labour and capital in the Northern Netherlands was very remarkable indeed. Nominal wages in the western parts of the country show a steady increase after the 1540s, leading by 1600 to rates that were consistently higher than those prevailing in Flanders and Brabant. Having stabilized about 1640, they still remained at a higher level than anywhere else in northern Europe until the beginning of the nineteenth century[69]. Interest rates, meanwhile, progressively declined from some 8 or 10% in 1600 to 2 or 4% around 1670, while rates in England, France and Germany at the time were still at least twice as high[70]. Given the rise in wages and the fall in interest rates, it was obviously a rational course of action for Dutch entrepreneurs to adopt labour-saving inventions.

But the development of technology in the Dutch Republic, as we have seen, encompassed far more than just the spread of innovations entailing an enhanced input of capital or energy and reduced input of labour. It also involved the growth of economic productivity by improvements in skills or the use of new combinations of natural resources.

This second route can to some extent be explained by the same factors as the first. Enhancing the `qualitative surplus value' of production can be an equally rational response to an increase in wage costs as the reduction of labour input. Indeed, there is no compelling reason from a theoretical point of view why the adoption of labour-saving inventions should be the sole reaction to a rise in wages[71]. And the alternative route was not without precedent in history. A similar move had been made, for instance, in the large urban centres of Flanders and Brabant in the Late Middle Ages. At that time, in cities like Antwerp, Bruges, Malines and Ghent, production shifted towards higher-quality goods and services. This shift, as Van der Wee has argued, should be understood as a very sensible response to the increased threat to traditional urban export industries from foreign and rural competitors. Given the prevailing high level of wages in the cities of Flanders and Brabant, it was a perfectly valid strategy for entrepreneurs and urban rulers to foster the growth of high-value production instead[72].

In the Dutch case during the seventeenth century, it was even more logical to pursue quality improvement because of two additional changes in production factor supply. First of all, the rise of the United Provinces as the leading emporium in world trade combined with the improvement of agrarian production at home and the expanded exploitation of inland natural resources gave Dutch producers access to a larger and more varied supply of raw materials of a better grade and at a lower price than any of their competitors in Europe, with perhaps the sole exception of Venice. Merino wool from Spain, marl from Tournay, silk from Bengal, lead from England, and rags from Germany ? in Holland almost everything was in ready supply. Having thus acquired a virtually unique command of natural resources, Dutch entrepreneurs were able to concentrate more on improving quality than were the bulk of their contemporary competitors (thus further advancing their position in world trade)[73].

But along with the carrot came the stick. While entrepreneurs in Holland were indeed favoured with an exceptionally rich and cheap supply of raw materials, they also had to cope with another increase in production costs that added to the already heavy burden of wages. The shift towards the employment of more fuel-intensive techniques was in a sense like a move from Scylla to Charybdis. Even if the share of wages in total costs could to some extent be reduced, the weight of the energy bill came to press all the more heavily. True, the Dutch economy was blessed with easy access to peat. But peat prices were almost continuously on the rise during the sixteenth and seventeenth centuries up to the 1670s, both in absolute and relative terms, i.e. compared with the general level of prices and wages[74]. Peat became ever more expensive. Demand was not just pushed up by the growing use of peat as an energy source for industrial production, but also by increased need of peat for home heating. Household consumption in the seventeenth century presumably rose even faster than before, owing to the rapid growth of population and the generally low level of temperatures in winter[75]. The problem could only partly be solved by a shift from peat to coal, as the costs of coal were on the increase as well[76]. And, despite the efforts of numerous inventors between 1500 and 1650, fuel-saving devices had probably not yet reached a very high level of efficiency. Thus the incentive for entrepreneurs to seek alternative strategies for reducing costs remained strong.

The emergence of innovations

Selecting and applying innovations is one thing; how and why they emerge is quite another. A change in relative

factor prices does not yet explain how the technologies employed came to be there in the first place. It would carry us too far to examine here the cognitive sources of all these innovations, but it may be appropriate to suggest at least a number of conditions in the Northern Netherlands that, taken together, probably constituted an extremely favourable environment for the introduction of new things, namely: skills brought by immigrants, political decentralization, lack of restrictions on experimentation, development of institutional arrangements concerning intellectual property, and specialization.

The huge influx of foreigners beginning in the late sixteenth century was perhaps the most conspicuous of the conditions favourable to innovation, but it was by no means the decisive factor. True, there was an immense movement of people from the Southern Netherlands to the North between 1570 and the second quarter of the seventeenth century, which ensured that most of the gains in economic productivity previously realized in Flanders and Brabant were suddenly and massively passed on to Holland, Zeeland and Utrecht[77]. The stock of knowledge in the Dutch Republic was further enlarged by successive waves of immigration of Sephardi Jews, the occasional influx of skilled people from Italy and England, and the large flow of Huguenot refugees from France from the 1680s onwards[78].

Even in the heyday of foreign influence, however, there always remained vast areas of technological achievement where the contribution of immigrants was of marginal importance. In the development of shipbuilding or drainage technology, for instance, the contribution of foreigners was close to nonexistent during the entire period of the economic expansion of the Dutch Republic. And, what is equally significant, in many areas of technology where foreign influence did carry some weight for a few decades after 1580, one later finds advances in technology that went well beyond the repertoire of tools, methods and devices initially borrowed from abroad. The roles in the transfer of technology even came to be gradually reversed. Ghent adopted the art of making *legaturen* from Haarlem in 1613; Cambrai twiners fetched their skills and equipment from Holland around 1650; Bruges, Brussels and Malines saw cloth and serge workers and entrepreneurs move down from the North in the 1650s and 1660s[79].

There were clearly additional factors at work that facilitated the upsurge of technological creativity in the Dutch Republic. David Landes, Eric Jones, Joel Mokyr and other economists have drawn attention to the general importance of political decentralization as providing a fertile ground for sustained innovation in technology[80], and this favourable condition obtained to a high degree in the Northern Netherlands as well, especially after the Dutch Revolt. As individual urban communities commonly vied with each other in improving the quality of local production or in attracting new economic activities that promised to increase the welfare and employment opportunities of their own citizens[81], inventors found themselves in a sellers' market. They could profit from privileges granted by local authorities and even play off one city against another. As long as this competition endured, creativity could thrive.

The growth of inventive activity was further aided by the relative absence of restrictions on experimenting. The circumstances that are thought to have stifled technological advance in Venice during the seventeenth century were not present at crucial times and places in the technological advance of the Northern Netherlands, or were at most of minor relevance. While guilds and local authorities in the Northern Netherlands, just like their Venetian counterparts, were strongly committed to protecting quality in production and employment opportunities for full citizens[82], they usually did not ? during the period under discussion at least ? prevent the introduction and application of innovations. Absence of restrictions could also result from the fact that there were no bodies with sufficient power to issue or enforce regulations on these matters. In the district of the Zaanstreek, which was the cradle of so many innovations in Dutch industry, guilds did not even exist. Local authorities in this region, which lacked formal urban status, had less coercive power than did governments of autonomous cities[83].

These conditions may explain why innovations in the Northern Netherlands long continued to emerge without obstacles. To understand why inventions actually did occur, one has to take the analysis yet one step further. According to the theory on economic growth developed by North and Thomas, innovation is encouraged by modifying the institutional environment to the extent that the private rate of return on the invention approaches the social rate of return. Individuals or groups will be willing to undertake substantial expenses for devising new things only if property rights to their intellectual products are reasonably ensured. If not, they will not be prepared to bear the costs of sustained research efforts. On the other hand, institutional arrangements have to be balanced in such a way that society, too, will reap the benefits of the inventions of individual members. If not, growth will not be forthcoming[84].

The most prominent example of such an institutional arrangement is a patent system. Although North and Thomas themselves in their survey of the economic history of the West do not stress the relevance of patents until they shift their focus from Holland to England, the granting of patents for invention was in fact quite a common practice in the Dutch Republic as well, as the following figures attest:

Table 1 *Number of patents for invention granted by the States General, 1589-1679*

period	number of patents granted
before 1590	9
1590-1599	36
1600-1609	55
1610-1619	81
1620-1629	118
1630-1639	92
1640-1649	39
1650-1659	26
1660-1669	38
1670-1679	24

Source: Doorman, *Octrooien voor uitvindingen*

The actual number granted was even higher than shown in the table, because patents were sometimes also issued by provincial authorities and town governments. Even so, the average number per year between 1590 and 1680 (5.6) exceeded that in other states for which regular series can be obtained, i.e. Venice between 1475 and 1550 (for industry only) (1.4) and the Southern Netherlands between 1598 and 1700 (0.6). In fact, the number of Dutch patents reached the same order of magnitude as that in England between 1660 and 1740 (5.5)[85].

Between 1590 and 1630 the system rapidly matured in the sense that both the private and social rates of return were reasonably well secured. The interests of private inventors were guaranteed by the granting of exclusive rights to put their innovations into practice, the penalization of offenders, and the liberty to treat patents as alienable property which could be bought, sold, donated or inherited[86]. The interests of society were safeguarded by fixing a term during which exclusive rights would apply (first usually five to twelve years, later settling on fifteen) and the obligation imposed on patentees to put their inventions into practice quickly[87]. And both sides could profit from the rule, which soon became standard practice, that inventors had to deposit a drawing, description or model of their invention with the authorities from whom they received their patent. Patentees could use these as evidence to fight off competitors, whereas non-privileged parties could employ them to expose fraud[88].

Even so, there have been many innovations in technology in the Dutch Republic that were not covered by patent law or by some other sort of protective arrangement[89]. This holds true both for improvements in quality (for instance in fisheries) and for technological advances that led to a rise in the physical productivity of labour (for instance in shipbuilding and the shipping industry).

In addition to immigration, political decentralization, lack of restrictions on experimentation, and the development of institutional arrangements concerning intellectual property, we have thus to consider one more factor that helped to create a favourable environment for the emergence of innovations in the Dutch Republic between 1580 and 1680: specialization. Specialization is of course a well-known source of technological advance. It facilitates in particular the opportunities for learning by doing. It proceeds the more easily as the extent of the market expands[90].

There is no doubt that specialization in the Northern Netherlands indeed grew apace in the sixteenth and seventeenth centuries, and most of all from the 1580s onwards, when the extent of the market increased immensely. Jan de Vries has discussed the technological innovations in the agrarian sector that followed in the wake of the expanding market. The growth of aggregate demand, I submit, pushed technological advance even further by facilitating the formation of groups that specialized in providing technological expertise. During the second half of the sixteenth century, Zeeland witnessed the rise of a select class of specialists in diking[91]. Haarlem saw the emergence of a group of ribbon-frame and twining-mill makers who (as a subsection of the guild of carpenters) by the early eighteenth century even demanded a special masterpiece as a precondition for admission[92]. And the number of people in Holland who were well versed in the art of the millwright must have risen significantly as the construction of windmills rapidly increased after 1600. On top of a growing `normal' need for windmills for drainage of existing lands, there suddenly emerged a huge demand for windmills for other purposes. In the Zaanstreek, the number of industrial windmills grew from virtually none in the 1590s, to c.40 in 1620, c.160 in 1640 and 584 in 1731[93]. The number of new *poldermolens* built between 1607 and 1635 for the execution of five large reclamation projects in the north of Holland amounted to no less than 170[94]. There were thus ever more opportunities for people to specialize in the making or repairing of mills. Small wonder that foreign observers in the early seventeenth century were so often

struck by the proficiency of the Dutch in the manual and mechanical arts.

5. Concluding remarks

Economic expansion in the Dutch Republic between c.1580 and 1680 would have been less impressive than it was, if there had not been a wide array of technological innovations in many sectors of the economy. The technological changes comprised far more than the massive employment of particular sources of energy. They were not just restricted to one or two sectors of the economy. Clearly, the advance took place across a very broad front.

The key feature is that many different sectors of the Dutch economy saw a remarkable growth in productivity over a prolonged period of time, due in part to the spread of technological innovations. The increase in productivity consisted in some cases primarily in a rise in the number of items produced per manhour, in other cases rather in an improvement in quality, and frequently in a mixture of the two. Future research will perhaps make it possible to express these gains more precisely in quantitative terms.

The advance in technology in itself may partly be explained by changes in relative factor prices and by growth in the extent of the market, which in turn led to more specialization. But innovations would never have emerged as easily as they did, if it had not been for the peculiar institutional context of the Dutch Republic.

NOTES

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20.. Unger, `Energy sources', 232-248.

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42.. Unger, *Dutch shipbuilding*, ch. 2.

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73.. This argument owes much to the points made by Israel, *Dutch primacy*, 356, 410, and L. Noordegraaf, `Nijverheid in de Noordelijke Nederlanden 1580-1650', *Algemene geschiedenis der Nederlanden* (Bussum 1980) VII: 82, 84.

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75.. See the data in De Vries, *The economy of Europe*, 12-13.

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84.. D.C. North & R.P. Thomas, *The rise of the Western world; A new economic history* (Cambridge University Press 1973) 2-7, 154-155.

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