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The importance of education and training policies in supporting technological revolutions: A comparative and historical analysis of UK, US, Germany, and Sweden (1830–1970)☆

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ABSTRACT

Major technological innovations are not sufficient to enable socio-economic progress without governments creating the institutional framework – in particular via education, welfare and training programs - required for the absorption of the new technical possibilities these innovations create. To support this claim, we provide a comparative historical view of how four different countries tackled the challenge of adapting to three successive technological revolutions, with varying degrees of success. We look at the relationship between the welfare, education and training policies implemented by the governments of the United Kingdom, Germany, the United States, and Sweden and their socio-economic results. The historical period studied spans from 1830 to 1970. This, according to the neo-Schumpeterian view we follow, covers the second, third and fourth technological revolutions, namely, the Age of Iron, Coal, and Railways, the Age of Steel and Heavy Engineering, and the Age of the Automobile and Mass Production; the current Age of Information and Telecommunications being the fifth.

1. Introduction: Technological revolutions and government policy for education and skills

Most recent studies of education and vocational training and their impact on technological progress focus on the second half of the twentieth century [1–4]. This paper attempts to fill the historical gap by providing a longer time perspective focusing on successive – and therefore different – revolutions and how various governments confronted the knowledge and skills destruction produced by each major upheaval and the creation of the new capabilities required in each case.

When identifying technological revolutions, we follow the neo-Schumpeterian view [5]; [6]; and [7]. This dating is similar to that of 'long waves' proposed by some economists, but in contrast to the recently popularised periodisation by Klaus Schwab [8] [1] and the notion of Industry 4.0. According to this perspective, the world is now mid-way along the diffusion path of the fifth technological revolution, the Age of Information and Telecommunications technologies, beginning with the microprocessor in the early 1970s and including the most recent new systems such as AI, robotics, or nanotechnology (Table 1), sometimes in coexistence with human work [9]. That interpretation has identified a historically recurrent pattern not only in innovation time per se [10], but in how technological revolutions propagate [7]. Each one emerges in response to the maturity of the previous one, leading to a period of financialised 'creative destruction' when the new technologies replace the old, more or less ruthlessly, in an increasingly unequal prosperity. The frenzy of the financial winners leads to bubbles ending in crashes,

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[1] For a detailed discussion, please see the first paper of this BEYOND4.0 project's work package (WP7), Perez and Murray-Leach (2021).

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followed by recessionary periods. The ills underlying the previous prosperity are then revealed and explode in resentment, revolts and populism. It is this disruption of the peace that serves as an alarm call to set up policies that will overcome the main ills of the earlier period. This is also in line with the argument by Kanger and Sillak [11] that 'meta-regimes' follow specific patterns. The subsequent 'golden age' unleashed by such policies is the time when governments shape the direction of the technologies, trying to spread the benefits of the new productivity potential across society. The whole process, from the initial radical innovations of the revolution until its last technology systems reach maturity, exhausting their potential for further productivity gains, new products and market growth, can be called a 'great surge of development', or simply a 'surge'. This is defined by Perez [7] as 'the process by which a technological revolution and its paradigm propagate across the economy, leading to structural changes in production, distribution, communication and consumption as well as to profound and qualitative changes in society'.

The reason why such revolutions deserve the name is their transformational power in terms not only of new technologies and leading industries, but also in the new forms of organisation, lifestyles, and something even more consequential –a change of techno-economic paradigm [12] and [7]. Essentially, it is a new and different common sense for best practice, influencing the direction of investment and innovation. Such a shift involves a massive change in the required skills throughout the surge.

Thus, one of the main features of each revolution is a combination of jobs and skills destruction and creation. As put by Su et al. [13]; 'the labor market can serve as a leading indicator for innovation and development'. The higher levels of productivity in the new industries, by definition, require less workers and different skills, sometimes lower, sometimes higher. The second technological revolution, the Age of Iron, Coal, and Railways, for instance, required, on the one hand, unskilled workers and children to serve the machines in the textile factories, displacing the remaining piece work artisans of traditional textile production; and, on the other, skilled workers such as iron smelter handlers, railroad specialists, telegraph operators, and accountants, on the other. The Age of Heavy Engineering, or third technological revolution, required truly skilled, highly educated workers in heavy engineering industries, as well as many others for simplified posts, soon to be redesigned with the time and motion studies developed by Frederick Winslow Taylor in the late 1890s and published in his 1911 book *The Principles of Scientific Management* [14], later to be simply called Taylorism. Something similar is happening in the current fifth revolution, with the demand for very highly skilled personnel for the highly technical coding and management jobs and the radical deskilling or outright elimination of many other jobs. In between them, the fourth revolution, or the Age of the Automobile and Mass Production, was characterised, in contrast, by the massive deskilling of the labour force, due to the Fordist assembly line, introduced by Ford in 1913, but also by the multiplication of innovative engineering fields to design the processes, supervise the workers and manage the growing non-assembly industries such as electricity and chemicals. Whatever the case, in each technological revolution there is a major uprooting of people, a disruption of communities and a separation of winners from losers in capabilities, territories, and welfare conditions [6].

At the same time, each revolution leads to a shift in lifestyles creating new needs and new demands, some of which are fulfilled with the new technologies, others with the revival of old skills, many with low productivity work. They are a central feature of the successive golden ages, such as the urban lives of the Victorian Boom the cosmopolitan lives of the Belle Epoque and the suburban lives in the Post-war boom. These changes accompany and result from the government policies that give direction to the revolutions in the aftermath of the midway recessions. They create many of the replacement jobs and the supplementary demand that will lead to a period of widespread prosperity and greater – perhaps full – employment [15].

According to that interpretation, the post-Covid19-pandemic world faces a major transformative moment, when massive institutional innovation will be required to change the playing field by proactively giving direction to the now well-known technologies. Not only is there an economic reconstruction, due to the many sectors that were affected, but the pandemic revealed the social inequality, the precarious working conditions of many as well as the lack of production resilience, from the pattern of globalisation. The re-directionality has historically involved policy innovations that reduce the social tensions generated by the 'creative destruction' nature of the first half of the diffusion process. Among them, adequate and subsidised education and training policies occupy an important place, together with welfare measures.

Our paper focuses on the education and training (and re-skilling) policies applied in the past 150 years, responding to successive technological revolutions, and touches upon welfare when appropriate and related. It draws on the experience of four countries, chosen for specific reasons. Firstly, it focuses on the UK, because it was the leader, or the prime mover of capitalist development, and core of the first two revolutions and therefore set the precedents for the economic absorption and shaping of major technical change. Secondly, it focuses on the US and Germany because they went from being followers, after Britain, to forging ahead by using a range of government policies from protection and subsidies to massive and specialised education. Finally, it focuses on Sweden, because it became an early follower in the third revolution and, by the fourth revolution, had become a pioneer in issues of welfare and worker training and education. In particular, this paper will follow each of the chosen countries – UK, Germany, US and Sweden – looking at the involvement of government in education, training, and welfare.

A foretaste of the comparisons is provided by Table 2, which shows the levels of basic literacy in each of the countries studied at the beginning of the 'golden ages' of each period. Even though Britain was already the industrial leader in 1850 (a year before the famous Great Exhibition), its level of literacy was lower than that of the other three countries studied, which accelerated their pace, intensifying education and training, counting on basic education.

Each of these results reflects public decisions and helps to bring

Table 1
Five successive technological revolutions, 1770s–2000s.

Technological revolution (surge)	Popular name for the period	Core country or countries	Big bang initiating the revolution	Year
FIRST	The 'Industrial Revolution'	Britain	Arkwright's mill opens in Cromford	1771
SECOND	Age of Steam and Railways	Britain (spreading to Continent and USA)	Test of the 'Rocket' steam engine for the Liverpool-Manchester railway	1829
THIRD	Age of Steel, Electricity and Heavy Engineering	USA and Germany forging ahead and overtaking Britain	The Carnegie Bessemer steel plant opens in Pittsburgh, Pennsylvania	1875
FOURTH	Age of Oil, the Automobile and Mass Production	USA (with Germany at first vying for world leadership), later spreading to Europe	First Model-T comes out of the Ford plant in Detroit, Michigan	1908
FIFTH	Age of Information and Telecommunications	USA (spreading to Europe and Asia)	The Intel microprocessor is announced in Santa Clara, California	1971

Source: Perez [7] Table 2.1, p. 11.

Table 2
Literacy rates for UK, Germany, US, Sweden (1850–1950).

Country	1850 Start of Victorian boom in UK	1900 Start of Belle Epoque in Europe Progressive Era US	1950 Start of Post-War boom US and gradually also Europe
UK	61.3	97	100
Germany	95	100	100
US	78	89.3	97.4
Sweden	90	100	100

Source: Steckel & Floud [16] (The characterisation of the dates is ours)

attention to different elements of the challenges facing governments today. Although it is not possible to make a single direct causal connection between educational interventions and the economic and social results, we can indeed note the recurring growth advantage of those countries where the government was more active in capability building. On this subject, Mazzucato and Kattel [17] recently showed the crucial role played by governments with extensive capabilities to learn and adapt in governing a crisis such as the current pandemic. This observation also reinforces the findings of a number of recent studies showing how better economic results can be achieved with better education [18,19], key to increase the capacity of systems to evolve.

The rest of the paper is structured as follows. Section 2 summarises the situation at the starting line of intense industrialisation, in the 1870s, when the Age of Steel and Heavy Engineering takes off. It aims to provide a comparative historical context across the four countries studied. At the time, Britain, as the industrial pioneer, had already experienced two technological revolutions whereas the other three were imitating and trying to catch up. In the subsequent four sections (Sections 3-6), we shall trace the actions each state took from the 1870s in the education and training spheres and how they propelled or hindered their ongoing development during the successive technological revolutions. Section 6 concludes and considers the lessons from the historical analysis for today's challenges.

2. The uneven alignment at the starting line (1830–1870)

2.1. The UK — the pioneering workshop of the world

During the 2nd technological revolution, the Age of Coal, Iron, and Railways, the UK was still leading the way as the so-called 'workshop of the world', with the US and Germany determined to copy what made the island so successful. In 1820, the UK's GDP reached $36 billion, against the $26 and $12 observed, respectively, in Germany and the US. GDP per capita was also much higher in the UK ($1707) compared to Germany ($1058) or the US ($1257) [20]. The original network of canals of the first industrial revolution had been overtaken by new railway and telegraph networks, which connected all parts of the country efficiently and quickly.

It should be noted that, in contrast with France and Germany, there were no high-evel engineering education in Britain. Much of the design and work was performed by engineers who learned under renowned masters (often in Europe) rather than in universities. Some of them, like George Stephenson or Isambard Kingdom Brunel became as famous as current 'rock stars' [21,22]. As indicated by the Institution of Civil Engineers (ICE), founded in London in 1818, and granted Royal Charter in 1828, "civil engineering hadn't really become an official profession yet" though there was training in the army and navy. Equally, the Institution of Mechanical Engineers, created in 1847, became an institution for sharing knowledge and experience among practitioners in the world of iron, steam engines and railways.[2] Where Britain was clearly strong in terms of training higher engineering skills was in all that related to shipbuilding to provide the Navy [23–25]. Although the more complex tasks were performed in the public sector, a private shipbuilding industry grew at its side serving private trade and military procurement.

While private investment in railways and industry flourished, city government taxes (and federal funds given to the cities) contracted out the building of roads, gas lighting, sewers and other service infrastructures to enable the flourishing of firms. In parallel, the 1846 repeal of the Corn Laws – the hated protective tariffs on cereals that made bread expensive – led the landowning aristocrats to shift to more lucrative crops or to collaborate with the financiers: so that political power gradually fused with financial capital and its interests [26]. Investment was also encouraged by the growing banking networks, which facilitated payments and access to credit everywhere. The UK's superiority was supported on the education of its leadership, thanks to the universities of Oxford and Cambridge, which offered highly specialised and quality education to the aristocracy, the members of the church, the leaders of the government and the higher-class military. On the other hand, through the East India Company, the British learned the Chinese tradition of 'professionalising' the civil service and gradually implemented the meritocratic principle in its selection system [27]. Unfortunately, while this was sufficient to let the prevailing industries of the second revolution thrive, it was not revolutionary enough, nor did it count on the appropriate higher education, to keep up with what proactive latecomers were able to do with the science-based, heavy engineering, possibilities of the following technological revolution.

2.2. The US — unifying the country with war and law in the Age of Coal, iron and railways

While the UK was prospering in the Victorian Boom of the second revolution, the US was still a developing country, sharply divided internally. The South was aristocratic, strongly connected to the UK through its exports of cotton and tobacco and preferring to import its industrial products in exchange. It was very different from the still relatively 'wild' West characterised by pioneering farmers. Yet they both coincided in opposing the protectionist Northeast, determined to industrialise, using tariff protection to keep prices high and confronting the British industrial and financial domination in the world market. In this purpose it was clear from early on that education and training would play an important role.

As could be expected, given its clear industrial orientation, the pioneer in guaranteeing mass education had been one of the North-Eastern states. As early as 1837 the Secretary of Education in Massachusetts inaugurated state-wide professional teachers. In 1852 the state passed the first universal public education law recognising the government's role in providing education for agricultural and industrial purposes. The example was later followed by other Northern states. This was reinforced by Lincoln, in 1862, granting federal lands to the states, with the express purpose of funding research and endowing higher education in the technical areas, from agriculture to industry, a focus that contrasted with the British tradition of liberal arts. That was the origin of the so-called Land-Grant universities of which the Massachusetts Institute of Technology (MIT) was one of the first. In 1869, again it was also Massachusetts that created the National Society for the Promotion of Industrial Education to prepare 'all men, women, and children' for a new type of instruction so as to avoid having American manufacturers

[2] The term 'engineer' in earlier centuries was applied to those who operated catapults or other military equipment and later to those who designed such equipment. The expression 'civil engineering' was then a way to distinguish designers of non-military equipment. Although the term was also used for those who operated steam engines on trains.

'competing disadvantageously with those of Europe' [28]. Other states and the federal government were gradually to follow suit. This was in parallel to the emergence of scientific curricula at military academies such as New York's West Academy, where colonel Thayer (1817–1833), had been one of the first ones to introduce studies of civil engineering [29], making military graduates responsible for dams, dykes, and the first railways all over the country.

While British industry saw itself as the unquestionable factory of the world, American manufacturers felt the pressure of competition and were determined to learn and surpass. The frequent international exhibitions, in Europe or America, helped both industrialists and government to see the technological frontier and to acknowledge the role of industrial education in benefitting employment and the growth of the economy. Yet, the North American powerhouse only managed to transform its entrepreneurial attitude into national leadership in 1865, when the Civil War achieved political union. In 1869, the railways coming from the East and the West finally joined, guaranteeing the physical union as well. Ironically, it was mainly British capital that funded much of the railroads, which served to unify the national market and help the US forge ahead. The boom that followed, similar to one in Germany, collapsed in 1873. But, in the US case, the recession did not lead to loss of confidence in the unfettered free market, especially because government promoted competition inside the country while it guaranteed protection against imports and, soon also, technical education.

2.3. *Germany — a taste of free markets without abandoning the learning tradition*

During the 2nd technological revolution, Germany was not yet a state, but a loose federation of states otherwise known as *Deutscher Bund.* In 1834, Prussia had led the formation of a customs union –the Zollverein – among the many German-speaking states, which only became a tighter Confederation in 1867. But such loose agreements lacked the necessary territorial stability to develop economically and technologically. It was in 1871, after the victory in the Franco- Prussian war, when the Empire was created following the unification of the country by Bismark, that businessmen founded the Deutsche Bank and introduced what were very lax joint-stock laws. From then on, funded by the war reparations, the push to imitate 'Manchester capitalism' (the term used for British style free-market competition) flourished and soon became an investment bubble. The boom ended in a major crash. The prolonged recessions that followed ended up questioning the superiority of the free market and moved Germany into so-called 'coordinated capitalism' [30], involving collaboration of banks and industry, state intervention and promotion of cooperation, later including cartels, and also farmer associations, worker organisations and so on, across the economy and society.

Due to the Prussian determination to claim political and intellectual leadership –be it for 'mercantilist impulse, […] military power, or incorporation of new people and territories' [31]– there had been a strong and active tradition of giving importance to science, technical skills, and education in general. Education for children aged up to 14 had been obligatory, municipally funded, and free for poor citizens in the state since 1763. As early as 1821, Prussia already had its first technical school in Berlin, while in 1825 the first Institute of Technology in Karlsruhe was established, inspired by the Parisian École Polytechnique., In parallel, research laboratories emerged everywhere during the 1830s [32]. Soon after, the foundation of the Association of German engineers in 1856 paved the way for an education with direct contact with the industrial world. Both scholars and the government acknowledged the advantages of promoting a scientific approach in education —including the teaching of courses such as mathematics, geometry, modelling, and the natural sciences at the simplest industrial *Handwerkerschulen*— 'to create a new and more attractive career path for the […] middle class' [33]. Investment in technical education grew in harmony with the increase in demand for technical professions, such as engineers. This was also in line with Prussia's intentions to dispose of excellent engineers as civil servants [34]. Contrary to the UK, it was the states who owned mineral rights in Germany. This meant, on the one hand, that private entrepreneurs were required to obtain permission to exploit them, as well as had to be supervised; and on the other hand, that the earliest engineering schools had to be mining academies. In general, the number of engineers with a higher technical education in the German territory grew from 166 in 1835 to 11,856 in 1870 [35]. Once unified under Prussian leadership, this emphasis on human capital put Germany in a good position to, first, copy existing British technologies, and, later, once having 'caught up', to forge ahead in science, technology, and engineering.

2.4. *Sweden – looking ahead from rural beginnings*

Inspired by Germany, the government of Sweden began taking measures from the mid-19th century to transform its basically rural economy into an industrialised one. It supported and collaborated with all providers of technical instruction in order 'to push the professional interests of engineers —and other technical figures— in the society further forward' [36].

First, school building was encouraged everywhere in the country. The 1842 Elementary School Act in the region of Sundsvall, for instance, required for each school district to establish at least one permanent school 'either alone or in cooperation with another parish' [37]. These were accessible to everyone and funded either through taxation in money and in kind or loans from individuals and banks. Second, a 'systematized' technical education was in place as early as the late 18th century [38]. In 1827 the KTH Technological Institute was established in Stockholm, with the introduction in the 1830s of numerous engineering courses —such as topography and road construction— in higher education. As a result of both public and private initiatives, in the 1860s students could study engineering already at the upper secondary level schools or start apprenticeships in private institutions such as the school of the Swedish Handicraft Association, opened in 1845. In contrast with the UK, in Sweden 'the fear of a shortage of engineers with adequate competences resulted in increased demands for alternative educational pathways and reformed programs in lower education'. Technical education was to be provided one way or the other.

According to Gerschenkron [39]; initial economic backwardness can result in more rapid rates of growth later on, due to the fact that latecomers are able to exploit technological advances, be it machinery, production methods, or lifestyles, without needing to destroy industries with obsolete techno-economic paradigms. The UK was undoubtedly leading the way in the Age of Iron, Coal, and Railways. However, the advantages of the latecomers emerged quickly when the second surge reached maturity and Germany, the US, and soon Sweden, caught up. In the sections below, we show that the culture of education, installed and developed in those countries, together with the appropriate welfare measures, played a significant role in confirming, or rather accelerating, such a turn of events.

These four countries then faced the 2nd technological revolution from very different starting points. The UK as the leader and most advanced, the other three beginning to catch up. The following sections will look at each of them in turn, seeing how their attitude and actions in relation to education and training before the 1870s, and then facing the third and fourth revolutions (from 1870 to 1970) determined their socio-economic results. The UK and education as a means of control.

2.5. *2nd surge 1830–1870 — becoming the workshop of the world with apprenticeships*

Following the 1st surge, or First Industrial Revolution beginning in 1771 with the emergence of the first machines and factories, the 1825 repeal of the Bubble Act, which finally allowed joint-stock companies in manufacturing, retail, and trade, and the 1830 opening of the Liverpool-Manchester railway line promoted by the mechanised cotton industries of the North-West, meant that the way was open for the second technological revolution in Britain. Railway networks became national, the telegraph overcame distance, and the population in the cities grew exponentially around the new manufacturing, driving the construction industry. Although the growth rates of just over 2% during the Victorian boom, between 1850 and 1870, were not very impressive, compared to those of other countries in similar golden ages, they were the highest at the time. But the underlying transformation can be seen in the changing sectoral shares. Agriculture decreased from 22.1% of GDP in 1841 to 14% in 1871. It was, of course, industry and services (including railways) that were taking over [40].

The major changes of the second technological revolution were undoubtedly political. The Reform Act of 1832 pushed by the Whigs, a political party that opposed absolute monarchy in favour of constitutional monarchism, reduced the political power of the aristocracy increasing the voting population by 50%. The political transformation culminated with the Repeal of the Corn Laws in 1846 —which put an end to landowners' tariff protection— and with the creation of the Liberal Party in 1859.

The beginning of the railway age in 1829, with 'Rocket' steam engine test for the Liverpool-Manchester railway, can also be seen as a shift in political ideology, from what was still a mercantilist parliamentary democracy led by the aristocrats and the imperial merchants, to a liberal free market economy increasingly led by the financiers and the industrialists. In 1834 the Poor Laws, as mentioned above, obliged individuals to sell their work in the market or go to the workhouses, so that, following a new capitalist ideology [41], education merely became 'an agency of social control' [42]. Thus, while politics modernised, the labour force was progressively deskilled. Where industrial, or technical, education was provided —especially at the end of the 1830s to educate children in the workhouses and in the 1841–52 with the School Sites Acts— this was to 'produce a level of education of practical use in the workplace' [43]. On the one hand, the new machines made work simple enough not to require specialised training or high levels of technical education. On the other hand, where specific skills where needed – including for manufacturing railway equipment, driving the trains, and managing the service – these were provided privately by the railway companies. At the end of the period, the 1870 Elementary Education Act did not make education free or compulsory, reflecting the government's lack of understanding of the importance of investment in human capital [44]. The 'strong emphasis on social control' typical of the early British education system [45] would lay the foundations for an elitist type of formation, later reflected in the routes shaped by Oxford and Cambridge [46].

During the 2nd technological revolution, a man was considered skilled if he, 'whether apprenticed or not, was capable of earning his livelihood at it and had become a competent workman' [44]. The concept of skill in the UK was more about character and behaviour and not necessarily related to education as such. So, the government was still reluctant to take on the necessary responsibilities to modernise and structure education in an innovative manner. In-house apprenticeships were inherited as a regularised practice from the Middle Ages: being the only means to give men the right to work in a particular trade, or guild, they were recognised as a proper institution. At this time, however, the British government was not yet actively committed to the provision of education, as education was still associated with religion. Competition and poaching of trainees only became an issue, with the much higher skills required in the following technological revolution. With industrialisation, the repetitive activity of assembling finished machine components became more and more common in British firms, so that not even apprenticeships, originally thought to increase workers' skills, were considered essential anymore [44]. In fact, many of the mills, especially textile, were handled by children.

The presence of rigid institutions strengthened by the governing elites' lack of social openness towards new technical figures [47] safeguarded an obsolete system of production —based on learning-by-doing and non-scientific methods [48] which was sufficient for its success in the Victorian boom. The expression 'tinkerers' is often used to refer to the engineers and innovators of the time. When the shift from simple manufacturing and machine-tending to science-based industry in the Age of Heavy Engineering occurred, Britain was not ready and inevitably lost its leadership position to highly educated competitors.

2.6. 3rd surge 1870–1914 — deskilling and technical education foretaste

In parallel with the bicycle and the typewriter allowing individuals to gain contact with the technical world in practical terms, the new cosmopolitan culture of theatre and journalism was accompanied by an industrialisation process based on cheap steel, electricity, and engineering. In 1907, the distribution of employment still showed manufacturing with a relative dominance (33.5%), followed by agriculture, which remained at 22.2%, the rest being transport, mining, finance and services. But, most importantly, within manufacturing, only 6.9% were in metals and 2.8% in chemicals. The majority were still in the industries mechanised in the second surge: textiles (38.6%) and food, drink and tobacco (8.8%) [49,50]. Meanwhile, the US and Germany were racing ahead in the metallurgical, electrical and chemical industries, and producing the required scientists, engineers and technically trained workers. As could be expected, then, British productivity also remained comparatively low. It is estimated that in 1909 an American engineer was almost twice as productive as a British one [49,50].

Regarding worker welfare, it is interesting to note that, in this period, several Quaker companies, among them Barclays and Rowntree, provided what was called 'welfare capitalism' [51]. It included housing, education, and childcare. This was in line with the Quaker idea that 'once it is impossible for a family to own their immediate means of production, the owners of such means have various ethical obligations to their workers' [51].

By contrast, the British government acted much later and only set up a timid version of the welfare state—introducing limited versions of old age pensions (1908), a minimum wage (1909), public employment agencies (1910), and insurance for sickness (1911). In this area, it was also behind Germany and other European countries. In fact, the strong free market ideology that prevailed allowed agriculture to decline significantly facing cheaper imports, let the protected industries of US and Germany to race ahead without much British competition and made it difficult to create a safety net for the majorities. It took almost ten years for the Liberal party to succeed in those partial elements of the welfare state, when, led by Lloyd George, it engaged in fierce parliamentary battles with strong resistance from the House of Lords.

There were also limited measures in the direction of educating children. The 1876 Elementary Education Act, for instance, prohibited employing children younger than 10; the 1880 Mundella Act guaranteed their obligatory education, and the 1902 Education Act created Local Education Authorities to oversee local school maintenance. Having said that, British liberalism was not as committed to education as their American counterparts, who were very conscious of the need to catch up with the British and from the 1880s onwards became more focused the social question [52]. In the UK, liberals had a much greater faith in the power of the market and were less prone to state intervention. Action was missing with respect to offering the technical instruction necessary for the new industries and technologies –according to the Royal Commission on Scientific Instruction, 'it had not been the policy of the State in this country to aid or interfere with the education of the middle classes' [53]. The terms of the statement are significant in themselves; government responsibility for strengthening human capital was not envisaged. Thus, philosopher Huxley warned that 'the latter years of the [19th] century promise to see [the country] in an industrial war of far more serious importance than the military wars' [53].

There were also isolated efforts by enthusiastic teachers such as Spencer, who in 1871 contributed to the establishment of an association for geometrical teaching. Similarly, while Oxford and Cambridge concentrated on educating aristocrats, the military leaders, the clergy and the rising bourgeoisie, other universities emerged trying to fill the gap for the excluded, be they of other religions (such as Jews, or some of the rebellious protestant sects) or of no religion at all. University College London, for instance, created in 1826 as a secular alternative, still faced many legal obstacles to be able to award degrees and even to be considered legally as a 'university'. However, it gradually evolved and, by the 1890s, it was emulating the Germans with high level education in science and engineering.

At the technical level, the government did begin to introduce reforms. The 1889 Technical Instruction Act, however, was ambiguous. It stated that grants would be administered locally under the supervision of the Science and Art Department, with no specification of technical education which had no clear skill profile nor an autonomous institution of reference. Neither was their funds a central concern. In fact, technical instruction ended up being funded by 'whiskey money'. Not knowing the destiny of the proceeds of a tax on alcohol – included in the 1890 Local Taxation Act – Parliament destined it to technical education. It was only in 1902 that the government recognises the crucial need for technical education and funds and enacts laws for local governments to identify and provide training in the required skills in their area [44].

The lack of a proactive government was accompanied by an ill-coordinated dynamics in British firms. New technologies in the working place, including 'screw-cutting, milling machines and the turret lathe', did not lead to the implementation of advanced technical education on the part of the state. On the contrary, they disfavoured the use of skilled engineering labour; made obsolete the institution of apprenticeship –one of the few institutions that provided vocational training; and encouraged the exploitation of low-skilled workers. The passive government and the traditional entrepreneurial system could count on a pool of 'process boys' specialised in a single repetitive operation and ignorant with respect to the 'fundamental principles of the trades in which they [were] engaged'. All this implicitly favoured traditional industries and discouraged the new ones, based on science and engineering, leaving the British economy behind [44].

But the lack of adequate education and training was related to the overall context. British industry itself was not prepared for a dramatic change in its ideology of production, characterised by the family firm and self-sufficiency. As explained by Payne [54]; 'the industrial structure of the United Kingdom had become so well established that further change was rendered extremely difficult', as were 'the possibilities of diversification, or branching out into entirely new lines of production'. Thus, the old industries prevailed, not requiring highly skilled labour. A London County Council report in 1909 observed that only 28.5% of the male working population entered skilled jobs and that even fewer (3.6%) required higher education. As a result, by 1910 in England, the number of university students in science and technology was about an eighth of that of Germany [55]. So, in a way, government was responding to what industry required.

2.7. 4th surge 1914–1970 — the formalisation of education

Following the First World War, the economic position of the UK was well behind latecomers Germany and the US. In heavy industry, for instance, between 1925 and 1939, there were only 630 large-sized plants (with more than 250 workers) in the UK, compared to 750 in Germany and 920 in the US [49,50]. Economic production in the staple industries declined during WW1 in favour of munitions and shipbuilding, which increased by a third in this period [56]. In parallel, the UK lost its international consumers, especially for coal: pre-WWI export volumes were still not recouped by 1929, when they were 80% of the export level in 1913 [57]. Overall, it was the UK that paid the highest for the war: the gross cost of WWI was equal to $44,029 million for Britain, compared to $32,080 for the US, $25,813 for France, $12,414 for Italy, and $40,150 for Germany [49,50]. This naturally led to extraordinary levels of unemployment and mainly so for coal miners, 'railwaymen, transport workers, printers, dockers, ironworkers and steelworkers' [58].

On the other hand, productivity rose significantly after the First World War (by 75% between 1914 and 1938), due to the technical improvement of machines based on special-purpose materials or processes [59] including in the cotton, steel, and iron industries. New industries emerged, such as automobile manufacturing, electrical engineering, and chemicals. However, 'British industry could not make the qualitative changes in technology, work organisation, and firm structure that were required to increase productivity in the long run' [60]. Some progress was made after World War Two, following which the UK did not suffer as much as the other countries: the gross costs this time were equal to $93,445 million for the UK, compared to $234,752 for Germany and $315,800 for the US [61]. During the 1950s–1960s recovery, several industries were nationalised, including steel, iron, gas, coal, and electricity. Demand for technical skills had increased during the war, when aircraft production had been given priority. But in spite of that, in 1950, the proportion of university students in the arts (37.2%) was still higher than in science (21.1%) or technology (15.8%) [60].

During the fourth surge of development, with the affordable free moving automobile, the process of urbanisation widened towards suburbia. With much cheaper land –compared to the third surge and the prior urbanisation–, mass produced components, more permissive land-use planning rules and accessible mortgages, a building boom ensued. The post-war construction boom and the demands of the new suburban lifestyle [15] led to the multiplication of semi-skilled jobs in building and to the emergence of many relatively unskilled ones in the service sector. This allowed compensating for the job losses in manufacturing, due to the introduction of the assembly-line. At the same time, growing companies in all sectors were requiring increasing layers of highly skilled managers as well as technical personnel to design and supervise production processes. But Britain was still behind.

At the beginning of the 20th century, according to British Liberal Prime Minister Lloyd George, German schools, 'not the[ir] arsenals' or submarines, represented the greatest international enemy of the country [62]. This was the time when the European model of formalised education, so envied by British scholars, began to gain relative momentum in the UK. First, the 1918 Fisher Act, extended the power of Local Authorities and allowed young workers to be entitled to day-release for education. Then the 1938 Spens Report encouraged the categorisation of secondary schools into 'grammar schools for the academically able; technical schools for those with a practical bent; and new 'modern' secondary schools for the rest' [63]. In 1944 with the Education Act, the three official categories of education we are familiar with today; namely, primary, secondary, and tertiary, were established.

This was also the time when serious welfare measures were introduced in the UK. The Beveridge Report presented in 1942, recommending social insurance and protection for all to fight 'Want, Disease, Ignorance, Squalor and Idleness' led to the founding of the National Health Service, providing free healthcare for all. Compared to the minimum intervention of the government during the previous technological revolutions, the progress achieved during this period was significant.

For quite a long time, however, technical education remained undervalued, in line with the traditional British cultural dichotomies between technology and literature, aristocracy and middle-class [60]. Only in a limited number of sectors were technical graduates required: From 1926 to 1937, class entries in motor car engineering increased from 4002 to 12,606 and, in electrical engineering from 14,527 to 25,944 [64]. Nevertheless, according to Sanderson [65]; even after World War Two, 'education continued to be a factor in poor economic performance'. The 'failure to develop the junior and secondary technical schools' led to a significant shortage of skilled labour in this period, when employers were still unaccustomed to hire university graduates. Surprisingly, following WWII, technical schools decreased significantly, from 319 in 1948 to 266 in 1960. As a result, in 1961, 20,000 vacancies for engineering craftsmen remained unfilled, intensifying the pattern observed in the interwar period. By contrast, the number of students obtaining university degrees had significantly increased compared to the First World War levels; the 4357 first degrees registered in 1920 almost quadrupled to 17,337 in 1950 [66]. However, the 'old-fashioned regard for the arts as more gentlemanly', encouraged polytechnics to resemble universities keeping the predominance of science over technology also during the fourth technological revolution [65]. In 1950, 90% of the English 'mechanical engineers' still did not possess a university degree [67].

In parallel, little advance was made with regards to training. With the 1964 Industrial Training Act, called by some 'a failed revolution' [68], an Industrial Training Board was established for each industry to provide guidance with respect to the quality and quantity of training offered in firms. However, employers still managed with difficulty to provide training to their apprentices or allow employees to leave work for studying during their day off [65]. In other words, technical education in formal educational institutes, such as schools and universities, was not sufficiently compensated by vocational education at the firm level. Attitudes toward education changed significantly between the second and the fourth technological revolutions in the UK.

While welfare reforms were implemented, several authors have pointed out [44–46] that education was still perceived as the formation of the ruling classes. In other words, it can be claimed that it was used as an elitist instrument for social control [42], rather than economic growth. At the same time, technical professions, such as those related to engineering, were discouraged by both the lack of formalised institutions providing rigorous technical education and the lack of demand for them on the part of employers.

3. The US forging ahead with protection and education

3.1. 3rd surge 1873–1917 — vocational education at the service of industrial growth

Between 1870 and 1913, the average annual rate of growth of productivity per hour worked in the US was 1.92%, against 1.22% in the UK, the original workshop of the world (Maddison, 2003), so that, by the end of the third surge, the US had already caught up with the UK (Table 3) (see Table 4).

The US government was focused on promoting industrial development across the whole country, now unified. High tariff barriers were erected, both for federal revenue – since no federal income tax existed before the late 1910s – and to protect companies while they competed nationally and gradually reached competitiveness in the world market. The other form of support for both agriculture and industry was the creation of universities for research and education. Recent experience in Asia has shown that both governments and businesses in catching-up countries are acutely aware of the need to implement own variants of tariff barriers to protect their markets, as well as acquire the technological capabilities possessed by the leaders. In the case of the early United States, the shortage of labour made it all the more urgent to apply whatever technologies could increase the productivity of the available work force. Engineering education was an obvious route to follow. The lack of federal income in the US made government use the vast expanses of land, acquired during the conquest of the West and in various wars and purchases, to fund the universities. The teaching, research and extension services of these institutions, across the country, became an essential part of the forging ahead process.

Table 3
Labour productivity US industrial sector as percent of UK (1839–1911).

1839/41	1849/51	1859/61	1869/71	1879/81	1889/91	1899/01	1909/11
159.8	162.7	152.8	145.1	146.3	167.8	170.9	186.5

Source: Broadberry & Irwin [69].

Table 4
Labour productivity in Germany's manufacturing sector as percent of UK (1895–1935).

1870	1913	1929	1938	1950	1973	1989
92.6	119.0	104.7	107.1	96.0	118.6	105.1

Source: [49,50]

Originally, the Morrill Land-Grants Act approved in 1862, during the Civil War, mainly benefitted the Northern and Western states. But the representatives of the industrial North wanted the Southern states to accelerate the mechanisation and modernisation of agriculture. Hence, in 1890, an extension of the Morrill Act (this time with cash) was directed at the South, and included making higher education available to all races, initiating a slow and difficult process that would take decades to unfold.

The accent on engineering gave impressive results. In 1866 there were perhaps 300 graduates from 5 colleges, by 1911, 21 colleges were graduating about three thousand engineers a year (compared to Germany's eighteen hundred). It is estimated that 38,000 were already in the workforce.

Given the heavy engineering nature of the third technological revolution, there was high demand for engineers and other technical professions. And, due to the continental size of the country, building infrastructures were giant projects and the availability of vast demand allowed standardised high-volume production leading to mammoth plants, with complex management hierarchies, before they appeared in Europe [70]. As a result, the various engineering specialisations became highly attractive and courses such as accounting, business mathematics, and marketing became more and more popular choices of education at university, whatever the profession. Furthermore, manual training was increasingly considered 'essential' by professors at technical universities — such as Woodward of the O'Fallon Polytechnic Institute at Washington University in St. Louis [70]— to prepare engineers and industry managers, or better yet, engineer-managers.

At the same time, workers were being trained mostly in apprenticeships inside the companies but also in many private educational initiatives. But labour became scarce as the economy grew, so immigration was encouraged and facilitated. The years between the mid-1870s and the mid-1890s were of constant deflation, due to globalisation and the productivity of the new technologies, so much did prices decrease that the period was known as 'the great depression' until the 1930s took over the term [71–73]. In those years around 12 million immigrants arrived in the United States, mainly from Europe especially Germany, Ireland and Britain, so that by 1900 they represented about 16% of the population [74]. Some were skilled but many weren't. There was competition for the skilled ones and in-house training for unskilled nationals and foreigners. Soon, poaching skilled workers became a serious problem and companies proposed that the government do the training. This was behind many training initiatives at the state level, but it took until 1917 for the Federal government to provide funds for vocational training across the country.

Evidence that reskilling the population had become the priority of the government was reflected in the fact that public expenditure for education overtook expenditures for health and welfare in this period. In an 1898 report, the president of the National Association of Manufacturers declared that the largest return to the American industries 'would come from the establishment of educational institutions which would give [them] skilled hands' [75]. As new professions such as typists, bookkeepers, or educators required the issuance of special certificates, educational facilities for industrial studies became state supported in several states especially after 1900, while many employees were also trained internally in firms [76]. In 1905, Massachusetts pioneered setting up a Commission on Industrial and Technical Education concerning skilled trades such as machine shop, printing, and construction [28]. It was followed in 1917 by its federal equivalent. In the American ideology, vocational and managerial training, more than technical education as such, had become the key instrument to achieve economic success. In the 20th century, as argued by Professor John Franklin Bobbitt, University of Chicago, in 1912, education was designed to guarantee a matching 'between individual capacities and job requirements' [75].

Up until 1904, the UK net output per worker was equal to £84.6 [77]. By 1909, labour productivity in America was twice that of the UK in most sectors. Holding labour productivity constant at 100 for the UK [49,50], found that American workers in metal manufacturing and engineering were, respectively, 2.88 and 2.03 times more productive. Meanwhile, employment had decreased in agriculture and mining, while increasing significantly in industry, transport, commerce, distribution, finance, and services.

3.2. 4th surge 1917–1970 — the time for differentiated education and training

In 1913, Henry Ford successfully implemented the continuous assembly line, which produced cars much faster than in shops and at a cheaper cost. His method inaugurated the mass production revolution that would destroy many of the jobs and skills that had been required for the fabricating industries, while continuous processing in chemicals, textiles, canning and bottling would do the same for the workers in non-assembly industries.

Mass consumption was soon encouraged by the credit system, at first provided directly by the automobile and radio companies and later by the credit card, beginning with the Diner's Club in the 1950s and followed by several others, widening their reach. But paradoxically what led the US to become the pioneer and emblem of the consumer society were the many welfare- and union-supporting measures that increased wages and maintained regular incomes with unemployment insurance and pensions. Most importantly for our purposes, during the fourth technological revolution the US government multiplied the public education system at all levels, including university-based professionalism, vocationalism and basic education for minimum skill jobs. In parallel, the domestic economy kept being protected; first, with the 1921 Emergency Tariff in favour of local agriculture, and then, after the catastrophic crash of 1929, with the 1930 Smoot-Hawley Tariff Act imposing historically high duties on imports of agriculture and 20,000 industrial products. Only with the 1948 GATT agreement, when the US economy was already leading the world in productivity, and had little competition, would tariff barriers be practically eliminated to promote free international trade.

Welfare and education reforms in this period were significant. In 1917, the Smith-Hughes Act established a Federal Board for Vocational Education and required the creation of vocational education boards in each state. In terms of worker protection, compensation for medical costs and workplace accidents had been adopted in 44 of the 48 states, by 1930. With the landslide victory of Franklin Delano Roosevelt in 1933, the depression was initially faced with the National Industrial Recovery Act aimed at agreements on fair wages and prices. Soon after, the 1935 Wagner Act, legalised the unions, established collective bargaining and allowed strikes as an accepted practice. The 1938 Fair Labour Standards Act then succeeded in setting minimum wages and maximum hours for most workers. It established the 40-h week and 1.5 pay for overtime.

The federal government's intervention in education for industrial purposes explicitly aimed to reskill workers who had been 'displaced by machines or new processes' [78]. The 1917 Smith-Hughes Act had enforced the formation of vocational education boards in each state along with the establishment of a Federal Board for Vocational Education. By 1921, expenditures in federally funded vocational education programmes had increased from \$2.68 million to \$10.65 million [79]. But the more intense efforts in spreading education to all were made after WWII, beginning with the so-called GI Bill, which guaranteed scholarships for all returning soldiers to further their education, including university level. Further funding was made available to vocational education programs with the 1946 George-Barden Act for agriculture. A decade later, the 1956 Health Amendment provided specialised education for nursing, while the 1963 Vocational Education Act assisted first-time job seekers or adults interested in retraining.

Given the experience of unemployment in the 1930s, a new type of assistance, focused on human capital investment, gradually became the norm in the US. Following the Second World War, vocational education became an instrument to fight unemployment, 'without delay' [75], among the millions of veterans returning, as well as a way to retrain the workers being shed by the defence industry. Roosevelt's interventions took into account the specific needs of American businesses, while supporting workers' rights and spurring national progress. Whether it was the significant investment in human capital, the complementary creation of government agencies, the huge electrification projects or the introduction of funds in favour of innovative agricultural machines, government intervention fostered the sectoral change observable in the US in the 20th century. Between 1930 and 1950, employment in agriculture dropped from 20.9 to 11%, while more Americans found jobs in the distribution sector (the rate increased from 11.7 to 18.7%) or started working for the government (from 7.2 to 10.1%) [49,50].

By the 1960s, when the gains in productivity attainable with further Fordist techniques –including assembly lines, semi-skilled workers, and dedicated machinery– were exhausted, a new threat to manufacturing jobs appeared with the introduction of robots for certain tasks in assembly lines. At the same time, the highly skilled jobs with machine tools in the workshops were being replaced by numerical control machine tools. This was also due to the dramatic contrast between better private schools and the more popular but worse state schools. If, on the one hand, 'the legacy of depression had served to heighten the country's sensitivity to the issues of unemployment and economic growth', on the other hand, 'the dawn of the Atomic Age had witnessed the implementation of a new technology that threatened to replace men with machine' [80]. A new type of assistance focused on human capital investment was progressively becoming the norm in the US. It then reached its peak with John Kennedy's Manpower Development and Training Act of 1962, put in place to retrain unemployed individuals in view of the emerging automation. In parallel, in-house training proceeded as before. Detroit's Packard Motor Car Company trained over 300 people for technical and skilled occupations, Dayton's Computing Machine Company provided training programmes on how to use the new machine tools and so on [78].

But, while manufacturing was shedding labour at the bottom, it was requiring more while collar staff to manage the giant corporations, soon becoming multi-national. Equally, more labour was needed in the multiple growing activities that served the mass consumption society. In view of this, the US government invested in training for commercial skills (including insurance and real estate), communications (including bookkeepers, secretaries, accountants, typewriters), all of which were also needed in the still growing public sector.

It is important to note that the essential principle behind Taylorist and Fordist methods —the first based on optimising movements and tools in the "one best way", the second based on splitting work into simple steps along a moving assembly line — was the separation of mind and hand. The knowledge and skills of blue-collar workers were to be controlled by management, who would determine the one best way, decide on the speed of the assembly line and otherwise define every other aspect of work, reducing the skills required and the time to learn them. Thus, labour in manufacturing was meant to be easily trained and easily replaceable. Inevitably then, during the 4th surge, the American educational system evolved to separate the leaders from the workers by providing a very sophisticated scientific, technological, and general education at the top and a very poor, standard education for the majority. This was in line with the Fordist principle that the blue-collar workers should 'leave their brain at home' and was justified, too, by the low levels of training that retail and other simple service jobs required. In parallel, technical education for skilled jobs, including machine tool operators or printing workers, was mainly provided in-company, while public training focused on the service vocations and on the main education system, from kindergarten to college. The system had several exit points, especially at 16, which was then the age limit of compulsory schooling. This basic education ladder was generally in the hands of state and local governments. The route to leadership was increasingly private, beginning with kindergarten, with its pinnacle at the top universities, which led the world league and increasingly attracted students from abroad. Ironically, the most advanced production methods provided by mass production ended up in an elitist system, which, though centring on science and engineering and management, became essentially similar to that of the traditional elitist system in the UK.

Having overtaken Britain after WWI, the US went on to lead the world as the financial, military and industrial power that helped the allied victory in WWII and funded much of the reconstruction of Europe. It led the subsequent post-war boom and, after exhausting the mass production revolution by the early 1970s, led both the information revolution and the globalisation process. Government efforts in adapting education and training to the specific needs of the economy were an important element in the success.

4. Germany: Moving forward with science, education and cooperation

3rd surge 1870–1919 — From agriculture to industry with the help of cartels.

During the Age of Steel and Heavy Engineering, Germany increased its tradition of corporatist organisation, with all industries and social groups tending to organise in cooperative organisations for mutual support and for bargaining with others. Along these lines, the main industries organised in cartels to control prices and quantities. The government both approved and encouraged such a form of group protection. Instead of obstructing productivity and innovation, as many would expect, cartels helped to increase its production volumes and productivity within the country, by avoiding price competition at home, while keeping exports competitive in both quality and cost. Cooperation between banks and companies – and of both with the education and training system – was encouraged by the state and led to Germany's leadership in electricity, chemistry and capital goods, all science-based industries. Exports soared in volume growing at an average rate of 4.1% per year, from 1870 to 1913, gradually reducing the difference with the UK that, already with the greatest empire, grew at 2.8% (Maddison, 2003).

After victory in the Franco-Prussian war, recently unified Germany set up a central bank, legalised joint-stock companies with lax regulation and promoted what became a major financial boom, in an unprecedented free-market experience, leading to a boom and a crash in 1873. The seven years of recession that followed convinced Chancellor Bismarck of the need to return to a proactive state, in order to protect its industries and working population from extreme economic risks. Among the many reforms implemented there was an even stronger commitment to the German tradition of technical education. This particular revolution required much more advanced and demanding skills than the previous ones. As a result of the modern technical approach taken by the education institutions, the number of engineers with higher technological education went from 11,856 in 1870 to 32,166 in 1890, reaching 59,738 in 1910 [35]. With such technical support, industry was soon able to replace agriculture as the largest sector in the economy.

The growth of industry came with rapid urbanisation and worker organisation. Together with tariff protection, Bismarck recognised the need to foster industrial peace by giving the workers, not only training, but also security. Unwilling to give the workers any power to form unions or to engage in collective bargaining or anything that would make them confront the owners, he concentrated on the health issues. In 1884 he passed the 1884 Damages Liability Law —making firms liable for any industrial accident— and this was soon followed by convalescent and sickness insurance and later by old age pensions paid half by employers, half by the workers and a top-up by the government. Thus, Bismarck's Germany became the pioneer of the Welfare State.

In order to avoid an excessive divide between the rural East and the industrialised West, farm research was promoted with financial and regulatory support, to help it adapt to technical progress [81]. But the central piece of the German industrial transformation was public education and training. Given that the third revolution was about the flourishing of the electrical, chemical and other science-based industries, the German government soon saw that advance was 'increasingly dependent on public educational and research facilities' [82]. By 1891 the government had accepted full responsibility for vocational training, which was reflected in the financial support granted to both the *Fachschulen* (specialised schools) and the *Technische Hochschulen* (Institutes of Technology).

A large number of studies were produced by the government on the relevance of the scientific method within industries. With the prevailing technologies at the turn of the 20th-century, in Germany there was a general acknowledgment that on-the-job training was not sufficient to make advancements in the electricity, mechanics, or chemistry. Advances were only possible by preparing highly educated engineers and researchers. As early as 1900, the country possessed 'the first industrial educational complex in the Western world' [67]. Germany became the place to go for advanced training among engineers and scientists from the US.

Officially recognised associations, such as the German Committee for Technical Education, founded in 1908, were born to institutionalise vocational training for future workers and provide intermediation with technical schools, which focused on engineering courses.

By 1899, technical universities were 'on equal footing' with classical universities and the salaries of highly trained technicians recognised this. This resulted in the steady increase of students in higher technical education in this period; from 5000 in the 1870s to 15,000 in 1900 [35]. The government widely encouraged the use of the scientific method based on 'mathematical precision, automatic processes, and scientific management' in the German companies. This meant trying to combine the deskilling methods of Taylorism with the high skilling requirements of science-based industries. The system assured the required training.

4.1. 4th surge 1919–1970 — skilled work for two post-war reconstructions

Germany assimilated the fourth industrial revolution with two periods of destruction, corresponding to the two world wars. Following the defeat in the first war, the enormous reparations that the young Keynes [83] rightly considered catastrophic and ominous led to uncontrollable hyper-inflation and economic chaos. This made the task of the recently created republic almost impossible and the difficulties experienced by the majorities opened the way to Hitler and his fascist nationalist party. He soon denounced the debts and engaged in intense industrialisation, at first, preparing for war and then, even more intensely during the war. After the second defeat, another industrialising effort – in what became West Germany – led to the 'German miracle' lasting until the mid-1970s, when all Western countries entered a period of stagflation, due to the maturity and exhaustion of the mass production revolution. We will look at each of the three periods in turn.

4.2. The Weimar Republic (1918–1933)

At the end of the First World War, Germany replaced the Wilhelmine empire with a democratic system. But the Weimar Republic faced massive financial reparations to the winners, leading to hyperinflation and depression. In 1923, one US dollar was equal to 4,200,000,000,000 marks [84]. Desperate attempts to raise taxes – a wealth tax in 1923 and a sales tax increase in 1930 – made things worse. In 1932, more than 6 million people were unemployed. In the middle phase of the Weimar Republic, welfare bills for the unemployed and social insurance recipients still constituted one third of local government expenditures [85]. 'In no other period of the 20th century did the costs of welfare weigh so heavily on the shoulders of local authorities as in [these] years'. In parallel, assistance to the young segment of the population was also offered, together with investments in health care and public works: care of the poor soon replaced welfare in the legal terminology [85]. Regarding education, the Weimar Republic established a four-year elementary school system (*Grundschule*) that was both free and universal [86]. Upon a small fee, pupils could attend the *Mittelschule* for an additional two years. However, no actual reforms were implemented with respect to higher education: in the midst of an economic crisis, it was not the government's priority. Following major public spending, the German economy was in desperate condition, despite only paying a small portion of the war reparations.

4.3. The third empire – the Hitler era (1933–1945)

While the Weimar government struggled to protect industry with exchange controls to curtail imports and to offer a demand-stimulus policy by financing public works, the leader of the National-socialist Party, Hitler, offered socialisation of the market, and the intensification of exchange controls and trade restrictions, invoking a strong nationalism [87]. The world was in recession since the crash of 1929 in the US. By the end of 1934, unemployment had dropped more sharply than anywhere else. Populism had reached the German folk and so had the leader's obsession for expanding training to strengthen the country.

Reskilling the labour force by investing in technical and specialised training became one of the German tactics to assert supremacy. First, the *Führer* granted industry and trade chambers the same powers of the *Handwerk* chambers to offer and certify training to industrial workers. Second, the National-socialist government supported the expansion of training workshops —which went from 167 in 1933 to 3304 in 1940— and vocational education to train both apprentices and skilled workers —numbering 244,250 in 1940— in preparation for war [88]. While teenagers and young adults had the possibility to work as apprentices in firms, for a certain number of days per week they were also allowed to attend courses in the so-called *Berufsschulen;* professional schools normally run by the government, or firms themselves. In parallel, guidelines by institutions such as the German Institute for Technical Education were followed thoroughly by firms —and almost militarily by engineers [33]— becoming increasingly relevant for modernising the economy. What was initiated during the Wilhelmine period continued during Hitler's dictatorship. Indeed, vocational training, including courses in physics, mathematics, technical drawing, astronomy, and handiworks intensified [88]; but not to the benefit of the workers. Taylor's scientific management and Ford's moving assembly line, copied from America since the 1920s, were at the core of the new work organisation, according to Hitler's idea of 'rationalisation', which meant the application of Taylor's systematic organisation methods, not just in the industrial companies, but also in military training [89]. The incorporation of Fordist methods was mainly done with the cooperation of the German subsidiaries of Ford and General Motors by a complicated set of regulations, including the prohibition of exporting profits, with the result that only investing in Germany was it possible to grow [90,91]. And the 1930's depression was a difficult time in America and Europe.

4.4. The post-war German miracle (1950–1970s)

After the defeat and destruction in WWII, the German economy had to be reconstructed. By 1950, employment in manufacturing, construction, transport, and distribution had increased by about 2%, and in government it went from 4.3 to 6.9%. By contrast, it had significantly dropped in agriculture by 10% [49,50]. Between 1950 and 1959 GDP rose annually by 8%, faster than in any other European country, and away from peasant farming [92], and so did exports [93]. Germany was in the midst of its *Wirtschaftswunder*, or economic miracle, guided by Ludwig Erhard, appointed Bavarian minister of trade and industry in 1945, then Federal minister of economic affairs between 1949 and 1963, and chancellor from 1963 until 1966.

Although the miracle was based on a strong welfare state and free markets, the public provision of education and training played a central role in supporting and promoting innovation, productivity and high tech. German schools maintained the dual system of vocational training and general education, and schools were still monitored at the state level. Regarding skilled work, the infrastructure created in favour of 'smart' education remained in place also. This was intensified with the Vocational Training Act of 1969, which established a strong network between the Federal Government and the *Länder*, or states.

It is important to note that, contrary to the US, the German industry maintained a high proportion of small- and medium-sized high-technology firms, the so-called *Mittelstand,* specialised in capital goods and complex products. It also had large companies in the processing industries – metallurgy, chemicals etc. – that required a highly skilled workforce. And so did the many in-house R&D laboratories common in large German firms.

Thus, although mass production methods were being applied at the Volkswagen plant and other large companies, the proportion of manufacturing requiring higher skills was significant and dynamic, so that the percentage of the workforce with at least an intermediate level of qualification continued to grow, surpassing that of workers without any qualification. By 1978 the proportions were 60.9% and 35.5%. As a result, labour productivity measured as GDP per employee in comparison with the UK (UK = 100) went from 66 in 1950 to 112 in 1973 [49,50].

Since the post-war period, the Federal government has been committed towards a legislation in favour of good living conditions for everyone in the country, including educational matters. The German *Länder*, more specifically, have always been fully responsible for schools, universities, and education, considered a state, rather than federal, responsibility. For the purpose of our analysis, the historical evidence suggests that one of the essential elements upholding the German industrial survival and success throughout these turbulent periods was the unwavering support of its education and training policies and practices by all political parties and by all of society.

5. Sweden and education for the Folkhemmet

5.1. 3rd surge 1870s–1910s — industrialising while protecting all the people

As early as the 1860s, Sweden began to change from a rural society into an industrialised and dynamic country. But the process was slow and the hope for better lives led many to migrate. It is estimated that more than a million Swedes went to America between 1850 and 1910 [94].

Guild monopolies were abolished when the country formed the Scandinavian Monetary Union with Denmark in 1873. Swedish society nurtured a tradition of social solidarity that gave importance to guaranteeing the *Folkhemmet*, or the People's Home, as Per Alvin Hanssen, the Social Democratic leader, called it in 1928. The term referred to the political concept embraced by the Swedish Democratic Party, as well as the Swedish welfare state itself, to guarantee social reforms for a society where everyone would take care of one another, like in a big family. This deep-seated tradition contributed to the development of enviable welfare reforms, together with development policies. Between 1870 and 1910 the growth rate in Sweden was significant in all sectors of the economy, albeit from a very small base. The manufacturing sector grew at 5% annually, transport and communication at 3.9%, and private services at 2.7% [95], with employment rising steadily.

As observed by Hort [96]; Sweden, in contrast with Germany, made an immediate shift from worker's insurance to people's insurance, following its solidaristic tradition. In this regard, in 1884, a mere four years after Bismarck began introducing careful welfare measures protecting workers in Germany, Adolf Hedin urged in parliament for a "new type of state involvement directed towards the labouring classes" [96]. His first worker's insurance bill provided occupational injury insurance, work accident regulations, and insurance for older workers as top priorities. The fact that the social insurance bill passed without opposition in the Swedish Parliament is emblematic of the fertile ground for social reform that was present in the country [96] both in the political world and outside of it. Next to student organisations such as Uppsala's Verdandi, an increasingly large number of scholars, including economists Knut Wicksell, Gustav Cassel, and social scientist Pontus Fahlbeck, wrote about factory legislation, welfare, and education [96]. As a result of such commitment, following the 1882 Statute of Schooling, by 1895, 99.9% of the Swedish population could read and write [97].

Most importantly, however, as is the case on most countries striving to catch up, the Swedish government understood that to become internationally competitive, education should serve the country's science-based industries with the highest potential of industrial growth [36] and, therefore, should become as scientific as possible. As a result of mass investment in training and education by the state, the number of engineers with a higher technical education degree almost tripled from 1121 in 1870 to 3145 in 1910 [36].

In addition to insurance and mass education, the Swedish government was able to prepare a workforce qualified for any type of job with *ad hoc* schools and universities. At the end of the 19th century, Sweden had already overcome the problem of mismatch of skills, while following an egalitarian political ideology.

5.2. 4th surge 1910s–1970s — the social democratic paradigm reaches its full potential

The fourth technological revolution did not start successfully for Sweden. Throughout the 1920s unemployment was high, around 10–12% [98], and conflicts in the labour market frequent. The election of the Social Democrats in 1932, however, paved the way for a new era of compromise. As the government guaranteed employment, while employers and trade unions "maintain[ed] industrial peace, set wage rates, and promot[ed] technical efficiency" [98], Sweden was advancing towards its golden age. It was in the 1930s when Sweden strengthened and diversified its steel industry as an important basis for further industrialisation. By the 1970s, the country was one of the richest in the world, with its gross national product per capita being surpassed only by the US [98]. Between 1950 and 1975, apart from agriculture, all industrial sectors were growing significantly, especially transport and communication (4.4%), private services (4.3%), and public services (4.0%) [95]. Its technological leadership in copper, gold and iron mining, established for centuries, was an important support for its advanced metallurgical industry [99,100].[3]

With respect to welfare, in 1913, the Swedish government eliminated the Poor Law Commission and established the National Board of Social Welfare together with the Employment Commission. Soon after, thanks to reformist labour politician Gustav Möller, Swedes older than 67 were provided with pensions as early as 1935 [96]. In parallel with social reforms, Sweden's government provided a highly proactive approach to the provision of skills to the workforce. They introduced the 1938 Saltsjobaden Agreement, which encouraged 'the institutionalisation of Swedish corporatism and vocational education training' [101]. The 1943 National Vocational Training Board favoured the labour force's 'adaptability' by boosting training in firms; and the 1955 reform on municipalities granted them 'a much prominent role in policy making' with respect to vocational schools and apprenticeships to satisfy local industrial needs [101].

An essential feature of the Swedish success from the 1950s was the adoption of the Rehn Meidner model [102]. It involved consensus building between government, unions and business to encourage innovations that would increase productivity. This was achieved by increasing wages across each sector, favouring high-productivity companies and forcing the less productive ones to improve or go out of the market. Support for alternative investment and retraining of the displaced workers would follow. Consequently, the model simultaneously achieved 'full employment, price stability, growth and equality' [102]. By the 1970s, Sweden had succeeded in increasing the standard of technical instruction, maximising social welfare and minimising inequality, while nurturing giant global corporations, and becoming one of the world's richest countries.

6. Conclusions

Every technological revolution has disrupted existing economic systems and forced changes in production, work, and lifestyles. The introduction of a massive set of new technologies, however, requires the proactive intervention of the state to bring about all its potential social and economic benefits. Over time, governments have been challenged by the need to set up a new institutional framework so that new techno-economic paradigms can be successfully absorbed, and its benefits distributed more fairly across society.

In this article, we have illustrated how governments in the UK, the US, Germany, and Sweden have operated to reskill their population in line with the new inventions, industries, and professions, as well as providing welfare measures to protect it from jobs and skills losses. Indeed, as rightly illustrated by Kohlgrüber et al. [103] in the BEYOND4.0 project's Work Package 6, 'any policy has consequences which go beyond the pure change of the skills mix of workers'. Specifically, we argued that governments' attitude towards education –including engineering and other technical specialisations– reflected their degree of interest in achieving 'scientific' industrial progress that would lead to a better future, even if this was to the detriment of traditional sectors in the short-term. Future research could address the role played by the specific differences in the welfare state models and the political colour of subsequent cabinets, which were not the main focus of this analysis, but likely contributed to political actions in favour or disfavour of education and reskilling policies.

While the UK can be considered the prime mover in terms of industrialisation, its unswerving faith in the free market at all times deprived it of public support for change when it was required. The government lacked the conviction – and therefore the decisiveness – to implement reforms in favour of reskilling the workforce for economic growth with major technological change while other countries were forging ahead. Although mass education was progressively replaced by specialised education for industrial purposes, the UK failed to tackle social inequality and to institutionalise technical education in favour of 'scientific' professions and industries. The control of education exercised by the Church of England thwarted many efforts by secular organisations or by those of other religions with legal restrictions. By the end of the third technological revolution, the UK was already lagging behind her latecomer followers. This shows that being the experimental cradle of major technological innovation is insufficient to guarantee leadership or institutional and economic progress. It is by providing the population

[3] Its expertise had already been confirmed in the early 1930s by successfully exploiting the low-grade Aitik copper deposit [107].

with the adequate education and skills that constant innovation and advances in productivity can be attained and a fairer society constructed. The UK case illustrated the danger that leading countries, accustomed to being ahead, may disregard the actions required to retain their front ranking position.

The latecomer advantage of the US, for instance, together with the shortage of labour, encouraged the government to invest in human capital to catch up and forge ahead of Britain. From the beginning, the more advanced American states provided education tailored to the industrial needs of the country, distinguishing between degrees of education and potential job opportunities. Technical courses and vocational training – be it publicly or privately provided – progressively became the core of the American education system. Nevertheless, the federal government succeeded only partially in levelling differences between states in terms of educational provision, and consequently in the resulting economic performance.

In Germany, that same latecomer advantage was enhanced by the creation of a welfare model and the provision of a wide range of training schemes and institutions for scientific and *ad hoc* technical education. The country was particularly effective in combining compulsory education with company training, supported by qualified teachers, contributing to reduce potential mismatches in the labour market. And having worker representatives in company boards facilitated understandings on the direction and intensity of technical change and the adaptation of the workforce in skills and conditions.

The objective of equipping skilled workers for skilled work was also achieved by Sweden, whose government guaranteed the social dialogue between employers, workers, and the state. Sweden eventually became a standard-bearer for how guaranteeing a social dialogue in the labour market and providing an efficient integration between education, training, and work can lead to significant economic success for business, together with social fairness.

As illustrated by the historical narrative provided here, the attitude of governments and institutions towards human capital investment is a relevant factor for absorbing new techno-economic paradigms. This supports the argument that technological change occurs in parallel with the development of technological knowledge [104], ultimately allowing for economic and social value creation [105]. The public sector can be a powerful reinforcement and complement to in-company innovation and training. And not just education in general, but one that guarantees the skills necessary for individuals and firms, and consequently the country, to advance with the new technologies, both socially and economically. As rightly stressed by Zamagni [106]; a true cultural revolution —which includes institutional, social, and economic change— can only be successful when work is accompanied by knowledge.

CRediT authorship contribution statement

Chiara Natalie Focacci: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Carlota Perez:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing – original draft, Writing – review & editing.

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