

BEYOND 4.0

- TECHNOLOGICAL REVOLUTIONS:
WHICH ONES, HOW MANY
AND WHY IT MATTERS:
A NEO-SCHUMPETERIAN VIEW

Historical Background Paper
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This paper provides a critical survey of existing studies on the relationship between technological revolutions and economic growth in the industrial era. Adopting a neo-Schumpeterian perspective which emphasises the interaction between technology, policy, politics and society, we outline a periodisation and criteria to identify successive technological revolutions and compare these with those proposed by other schools of thought. These include economists, historians of economic thought and technical change, neo-Marxists and business, management and engineering scholars. We argue that the differences in interpretations stem from the focus and premises adopted by each author and from the types of interactions studied and highlighted. The way technological revolutions are defined is important because it leads to quite different policy implications. A neo-Schumpeterian perspective widens the scope for policy intervention by admitting a potentially powerful role for the state and society in determining the trajectory of technological revolutions in their deployment phase, in contrast to technological-determinist perspectives. To illustrate this argument, we compare in detail the policy implications of Klaus Schwab's influential 'Industry 4.0' concept and the neo-Schumpeterian analysis of the historical regularities in the diffusion of technological revolutions. We conclude that while complementary, the neo-Schumpeterian approach provides broader criteria for shaping politics and policy making in relation to technology, social wellbeing, employment, skills and sustainability.

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Executive Summary

This paper is the first of three to offer a historical perspective on technological transitions for the **BEYOND4.0** project. Part of that task is to interrogate the theoretical basis underpinning the very concept of **BEYOND4.0**. The project takes its name from Industrie 4.0, a term popularised by Klaus Schwab (2016) via the World Economic Forum. This fourth ‘technological revolution’ has been heralded by some as the saviour of our futures while perceived by others – sometimes in tandem, sometimes opposingly – as the cause of job and skill losses, regional declines and further threats ahead. Over the past decade, this concept has gained significant traction in discussions of our current technological transition, despite not being well defined (Kowalikova et al., 2020).

Thus this initial paper maps out the timeline of technological change and its socio-economic impact since the start of the industrial era, but does not take the periodization of this timeline as laid in stone. Rather, it undertakes a critical survey of existing studies on the relationship between technological revolutions and economic growth in the industrial era. It provides a primer on the different ways in which technological revolutions have been conceived and analysed, and the implications of taking one theoretical approach over another. And it critiques in depth the ‘Industrie 4.0’ concept and looks at how it might be improved as both an accurate picture of technological history and a heuristic device, moving away from technological determinism and widening the scope for policy intervention by the state.

The main premise for **BEYOND4.0** is that technology is not deterministic but socially negotiated by key actors, and that this premise opens up the possibility that the EU can use digital technologies, those often grouped together under the banner of Industrie 4.0, to promote the creation of an inclusive economy that provides decent work and lives for EU citizens. The objective of the historical work package (WP7) is to provide insight into the process(es) of technological transformation at a societal level. It aims to analyse the effects of previous technological revolutions on employment and labour markets, business models and social welfare, in order to inform policy prescription in the present.

It is now understood that technological innovation is a key driver of progress. Nevertheless, seldom do policymakers or academics go beyond a general notion of innovation to fully grasp how technologies evolve, inter-relate and are absorbed, shaped, and diffused across society and the economy. What is gaining ground is the recognition that technological advance is not continuous but is rather revolutionised every time the economy confronts maturity via a series of interrelated innovations that explode and lead to periods of ‘creative destruction’.

Each such revolution has required deep changes in government, institutions, and policies to shape the new technologies for the benefit of both business and society. Building on the project Guidance Paper (D2.1; Warhurst et al. 2019), this paper focuses on how these technological revolutions are understood. There have been many attempts to identify such techno-economic cycles in the history of capitalism, by economists and historians, innovation scholars and engineers, business gurus and beyond. Adopting a neo-Schumpeterian perspective which analyses the feedback loops of transformation between science, technology, the economy, society and politics, and emphasises

this interaction between diverse social actors, the paper outlines a periodisation and criteria for identification of each transition, and compares these with those proposed by other schools of thought.

The paper argues that the differences in interpretations stem from the focus and premises adopted by each author and from the types of interactions studied and highlighted – and that the way technological revolutions are defined is important because it leads to quite different policy implications. Many of the current commentators are concentrating on the initial – and often negative – consequences of the new digital technology, whether that be standards of living and/or employment. Even if generally positive about the future, their policy prescriptions are oriented towards mitigating these negative effects. Unfortunately, both techno-optimist and techno-pessimist approaches can inadvertently lead to techno-determinism; the way in which they periodize and interpret previous transitions means that they do not recognise the capacity or the need for government policy to shape the course of technologies, which in their view is inexorable. And because they do not grasp the complexity and depth of change that each revolution brings, the policies that result are little more than bolt-ons to business as usual to a model that derives from the previous mass production era.

By contrast, Schwab and other 4.0 advocates take a more proactive, non-deterministic stance that recognises the complexity of interactions between technologies old and new and the role and impact of multiple actors across society. Although missing the solid grounding of a historical model of how technological change takes place and why and how society has absorbed and shaped similar transformations in the past, they signal the need for debate to move on from a modified business-as-usual perspective to the need for a more radical 'Great Reset'.

This paper adds that historical model: a deep analysis of the historical record which shows that the development and diffusion of each new technology follows a context-dependent direction, and one which is 'directed', intentionally or not, by social actors. It lays out in detail the policy implications of the 'Industry 4.0' concept alongside the insights provided by the neo-Schumpeterian analysis of the historical regularities in the diffusion of technology, drawing also on the work of the Dutch Transitions school on socio-technical transformations. This combination of perspectives in **BEYOND4.0** widens the scope for policy intervention by highlighting the potentially powerful role for state and society in determining the trajectory of technological revolutions in their deployment phase, providing a broader criteria for shaping politics and policy making in relation to technology, social wellbeing, employment, skills and sustainability.

1. Introduction

BEYOND4.0 takes its name from Industry 4.0, a term coined at the turn of the last decade to promote the technological upgrading of German industry and popularised by Klaus Schwab (2016) via his leadership of the World Economic Forum. Over the past decade, it has gained significant traction in discussions of technological or industrial revolutions, despite not being well defined (Kowalikova et al., 2020); according to Schwab, it relates to cyber-physical systems, whereas to others, it relates to advanced ICT and/or AI and robotics. Either way, this fourth revolution has been heralded by some as the saviour of our futures while perceived by others – sometimes in tandem, sometimes opposingly – as the cause of job and skill losses, regional declines and further threats ahead.

However, **the definition of what makes a technological revolution is not clear and established.** Since the mid-eighteenth century, academics and policymakers have been intrigued by repetitive historical patterns of economic growth and decline and the links between these patterns and major shifts in the socio-economic context. For some of those scholars, the influence that technological change has played in these shifts has been a key area of interest. Yet **different schools and authors have identified different numbers of revolutions and provided diverging interpretations of their nature and consequences.** Whilst there have been some attempts to outline definitive historical periodisations with categorical ‘empirical evidence’ (see Section 3.1), these have not resulted in any watertight conclusions. We hold that it is not actually possible to judge what are, in fact, theoretical frameworks as correct or not, because they are, precisely, theories – and each one focuses on a particular question, or set of questions and goal, and uses a different lens to interpret and slice history.

Thus, what we hope to do with this background paper, a critical survey of the study of the relationship between technological revolutions and economic growth in the industrial era, is not to discuss the validity of the different interpretations, but rather to identify the point of view that leads to each periodisation. **The goal is to broaden our understanding of the notion of technological or industrial revolutions, and to consider the impact that different approaches have on the application of history to our understanding of the present and the future.** We argue that ultimately there are clear advantages to complementing Schwab’s concept of Industry 4.0 with a neo-Schumpeterian interpretation; **one which emphasises the role the State and wider society can play in shaping technological progress,** specifically when it comes to policy design in relation to skills, employment and their relationship to social wellbeing.

The paper is laid out as follows. Section One is a discussion of our approach to the literature review and a brief description and summary of the broader literature and popular discourse survey work that was done for Task 7.1, the detailed findings of which can be found in the extensive Appendix to this paper.

Section Two is a detailed summary of the key contributions. The interpretations of economists studying growth – Kondratiev, Schumpeter, Kuznets, Maddison and others – are contrasted with the periodisations made by economic historians – Landes, Mokyr – and by those focused on the

consequences of technical change – R. Gordon, Frey and Osborne. We also cover the input of Marxist scholars – Hobsbawm, D. Gordon, Bowles; of those concerned primarily with socio-technical transition processes – Geels et al.; and the analyses and predictions of the future of technology focused on the worlds of management and engineering, such as Brynjolfsson and McAfee, Schwab and others.

Section Three is a summary of the neo-Schumpeterian approach and includes a detailed primer on the dating and content of each technological revolution: the associated raw materials, general-purpose technologies, infrastructures, and organisational forms; the periods of installation, bust and boom; and the defining ‘lifestyle’ that has aided in the positive-sum deployment of the new technologies for business and society.

In Section Four, the paper argues that the differences in interpretation stem from the focus and premises adopted by each author and from the types of interactions studied and highlighted, with a particular warning regarding the tendency towards technological determinism and the importance of understanding the role of society in shaping the direction and diffusion of technology.

Finally, Section Five compares the Schwab and Neo-Schumpeterian approach, concluding that they are complementary. The paper holds that the way revolutions are defined leads to different policy implications, and that is why the interrogation of theoretical notions is crucial; our primary objective will be to compare the way that each of the models understands the nature of the revolution and the power of society to mould it, believing that understanding defines the capacity to guide policy action effectively.

2. Approach to the literature review

2.1 Aims

The overall aim of Task 7.1 is to identify the key intellectual threads in the theories of technological revolutions; critically analyse how scholars have used historical data to periodise history and, by doing so, forecast the future; and provide a brief primer on the historical facts on which those theories rest. Our claim is that the choice of periodisation is key in applying lessons from history to the present, and risks obscuring more than it reveals.

This paper takes a specific perspective to technological revolutions, namely, a neo-Schumpeterian one, and foregrounds critical analysis. However, the more general survey of literature – based on manual and systematic searches of relevant journals, academic databases and access points to the popular discourse on technological revolutions – can be found in the Appendix of the paper.¹

2.2 A Nota Bene

Initially, we hoped to undertake a meta-analysis of the historical data used within the studies of technological revolutions: on the fluctuations of economic growth, productivity, industry and sectoral changes, and so on. This cross-analysis could then both be discussed in the current paper, and used where relevant in Tasks 7.2 and 7.3. However, during the initial stages of the research for this paper, it quickly became apparent that the data available is so scant – and contentious, amongst economic historians – that even research into single industries and/or short periods of national technological change by economic historians dedicated to those areas has led to notoriously conflicting interpretations.² Furthermore, where available, **the very different ways in which data has been used and periodised in the diverse works under discussion here are precisely the point of the rest of this paper: that it is the framing of such data that is key.** Such conflicts of approach shall be discussed below, and gaps and conflicts in the data itself covered where relevant in D7.2.

2.3 Selection criteria

Many systematic reviews claim in their methodology that they first cast the net wide, and then winnow articles down for inclusion by various criteria - themes, keywords, publications, and so on. Others admit to a more iterative approach, such as the ‘snowball’ method, in which the bibliographies of papers are scanned for further papers. We did use the latter in the course of

¹ This section would be reduced significantly for a published paper. However, we think it useful to include for internal circulation amongst the Beyond 4.0 team, and for the EU version, as it signposts to the extensive survey work of the rest of the task.

² See, for example, Crafts (2004), on the long debate around growth accounting in the British Industrial Revolution, with conflicting figures from four groups of scholars in Table 1, p.21 of the 2002 working paper; three in the published article (p.522).

casting our own net wider, adding to a list of key authors from across different disciplines and schools of thought, based on discussions in Dosi et al. (1988), Freeman (1996) and from the principal investigator's decades of work on the topic. This initial list provided us with key terms, concepts, disciplines and journals to investigate via database searches to ensure that authors were not omitted and that those included did indeed show up as high impact. In the Appendix, we discuss our findings from searching the key terms and concepts that we selected in the Web of Science and EconLit databases; the journals Technological Forecasting and Social Change, Futures, Evolutionary Economics and others; Google Scholar, and of authors' Amazon rankings. We also track the use of the terms 'technological revolution*' and 'industrial revolution*' over time, using both Google NGRAMs and data from the corpus of Scientific American.³

It is worth emphasising here that the literature reviewed in this paper is primarily theoretical, despite, often, underlying assumptions to the contrary. This is repeatedly ignored in discussions of Industry 4.0 or 'a fourth industrial revolution', and this is one of the points that we wish to make in our discussion. Certainly, the scholars base their periodisation on (typically limited) sets of data, but the periodisations are either their own or inherited from the school of thought that they follow. In the 1980s, in the midst of a flurry of work on economic cycles, young scholars wrote enthusiastically of 'new evidence [that] has been established' in the previous decade to prove the start of a fifth long wave (Mosekilde and Rasmussen, 1986); today, in 2021, their equivalents write with certainty that we are in the 'Fourth Industrial Revolution' without defining what that means or citing any sources, let alone data to support the notion. Thus, the work of this Task has produced, as a Deliverable, primarily a background paper to an idea; an intellectual history of the concept of 'technological revolutions'; and a piece of critical theory.

And yet, we have attempted with this paper to carry out the same aim as systematic reviews of large volumes of empirical studies – to make sense of multiple pieces of work on the same topic; to analyse not only what questions those studies answer, but also to look at what are the questions that those studies ask; and, crucially, 'to flag up areas where spurious certainty abounds' (Petticrew and Roberts, 2006). What is crucial is to consider to what aim each scholar is using their periodisations for; what is the theoretical framework that they have built with the empirical data that they have selected? As we shall address at length in the concluding Section 6, **the choice of periodisation is as key to the analysis as the data itself.**

2.4 A note on terms

Whilst we go into this more deeply in the Appendix, it is important at the outset to consider the terms used. **'Technological revolution/s' has become a slippery concept, used across different academic disciplines and, increasingly, in popular discourse.**⁴ Therefore, our first task in attempting a search of the literature was to wrestle with the problem of a term typically so poorly defined. As we show in the Appendix, a researcher attempting to grapple with the history of the literature, with little or no prior knowledge of its lineage, would not get very far by inputting the phrase

³ Provided for this paper by Dr Frédérique Bone and colleagues from the Deep Transitions project at SPRU, University of Sussex.

⁴ See also Section 4.1 of the project's 'Guidance paper on key concepts, issues and developments', D2.1. This paper, D7.1, expands on the discussion started in the Guidance paper, a conceptual framework guide produced at the start of Beyond 4.0 as a reference point for all members of the consortium (Warhurst et al., 2019; pp. 9-14).

'technological revolutions' into one of the databases. That phrase has gone through phases of popularity, but each time its use has had a different focus. It is also only one of a number of terms used in this type of analysis of technological change. As discussed in the Introduction, currently dominant is the phrase that originated as a business catchphrase, 'Industry 4.0'. Other scholars talk of 'long waves' – another very slippery term, meaning quite different things to different users – cycles or surges of development. The lack of a common definition of all these terms is something that we shall discuss further within the paper, as **it is this very looseness that both confuses and allows each user to make different/competing/unfounded claims.**

2.5 Categories

Apparent from the initial shortlist and confirmed by our research were the variety of disciplines that have undertaken the study of technological periodisations. By its nature, **it is a topic that requires the skills of the cross-disciplinarian**: sociologists become economic historians, economic historians, anthropologists, management economists sociologists. Thus in writing the review, categorising by discipline alone seemed insufficient. Furthermore, as already discussed, **a key question is to what aim the writer is employing their periodisations. Thus, we have categorised the literature into seven primary perspectives.** Although not bound by discipline, different types do predominate within different fields. It should be noted that these categories are useful shorthands chosen by the authors of this paper and not definitive schools to which the scholars themselves subscribe.

3. Different definitions of technological revolutions: what, how many and when

Progress in capitalism is most frequently associated with technological advance, both in more efficient methods of production or transport and in new life-changing consumer products and services. But there are times when there seems to be an explosion of innovation and technology, which becomes very visible, and times when advances appear as commonplace. Since the 1970s with the microprocessor and especially since the mid-1990s, when the US government handed the internet over to the private sector, **the feeling that we are in the midst of a ‘technological revolution’ has become widespread. This has naturally led to attempts to understand these major bursts of innovation and their effects on the economy and on the fate of countries, as well as their impact on employment and daily lives.** Since a similar explosion of innovations took place from the 1870-90s and another from the 1920s, it is no surprise that there was a burst of theories and studies about such phenomena then. **And yet, the differences in interpretation and dating among the various authors who have worked on the topic are significant.**

In what follows, we will briefly summarise the various interpretations and periodisations, classifying them by what can be seen as their central focus and point of view. The first is that of **economic cycles and long waves**, arguably the perspective from which the periodisation of history to better understand economics in the present emerges. The second perspective covers the **historical view** of technological revolutions, and includes both dedicated economic historians and economists of the present who take a strongly socio-historical approach. The third is the **business, managerial and engineering approach**, which predominates in the popular literature. Fourth are the **neo-Marxist contributions**, which look at how technologies shape the power relations in the production and distribution process. Those ascribed to the fifth perspective privilege **innovation** in their analysis, taking an analytical path between Marx and Schumpeter.⁵ The sixth category summarises the input of those who study **technological transitions at the meso-level**, but whose work has greatly informed the study of societal technological revolutions. Finally, the seventh perspective deals with that of the **neo-Schumpeterians**, who analyse the feedback loops of transformation between technology, the economy, society and politics.

As Kleinknecht wrote in 1987, in the middle of a surge of scholarly work on the topic, many have noted ‘that even the discussions on long waves seem to represent a cyclical pattern’ – and that while under scrutiny in the 1920s and 30s, ‘during the euphoric growth period of the 1950s and 1960s they were relegated to the background of economic literature’ (Kleinknecht, 1987, p.1). After the renewed interest of the 1980s⁶, there was once again a drop in interest, kept alive by K-wave econometricians (K derived from Kondratiev; see section 3.1 below) and in the work of evolutionary

⁵ Note that there are scholars in other categories who would consider themselves political aligned with the Marxist tradition – particularly from within the ranks of the long-wave scholars - but who write on this topic from a broader school of thought.

⁶ See, for example, the special issue of *Futures*, August 1981, edited by Christopher Freeman and ‘with contributions from virtually every major student of the subject’ (Onuf, 1984).

economists, the primary author of this paper included. Now, the technological revolution as a concept is back, growing in popularity – slowly at first – from the 2008 crisis, dominated by the perspective of German industrial policy and the World Economic Forum, but accompanied by other popular framings. We attempt to summarise the shifts in these patterns of scholarly work on the cyclical patterns of history here/in Section 2; further details on the dating and content of these scholarly surges can be found in the Appendix.

Our aim here is not to delve back into the murky depths of the by now century-old debate on the statistically empirical ‘reality’ of long-waves as measured by prices, output, employment figures or the like. We shall touch on some of this data in later papers for the project. **This background paper, however, focuses on the impact on our understanding of the present – and our policymaking – by choosing to use one or another theoretical framework, at a time when ‘the Fourth Industrial Revolution’ is being taken as a given by academics and policy makers with almost no empirical grounding.** Besides, such statistical wrangling over the K-wave has already been done in far more detail than we could do here, and, as we discuss in the section below, though in less volume than 20 years ago, continues to be debated.

3.1 The cyclical ‘long waves’ approach: the economic view

One element of the technological revolutions debate to be aware of is the blanket **(mis)use of the term ‘long waves’**. It has often been used as shorthand to describe the periodisations of history by economists, sometimes interchangeably with ‘business cycles’; indeed, ‘wave’ was a mistranslation of long cycle from the Russian (Freeman and Louça, 2001; Tinbergen, 1981). This broadening of the notion is understandable, given the place of long-wave studies in economic history. While most mainstream economists have viewed the longer periodisations as not much more than an amusing or annoying diversion from standard equilibrium theory (Onuf, 1984; Mathews, 2013) – although they do accept the recurrence of recessionary periods between bouts of growth – vague notions of the real world presence of some sort of cyclical pattern to profit and loss, growth and recessions have stuck. From the beginnings of capitalism in the industrial revolution of the late 18th century, it was noticed that market economies went through cycles of various lengths and a few economists – and politicians and businessmen – have repeatedly tried to find an explanation for such events.

Clément **Juglar** (1862) is noted as a pioneer, although his work built on that of contemporaries who today go unrecognised (Besomi, 2009). He sought to explain commercial crises by identifying 7-11 year cycles in investment, complete with four phases (prosperity, crisis, liquidation and recession). Working at the same time, William Stanley **Jevons** (1884) is also often (somewhat mis) credited as ‘the first’ to recognise business cycles; he noted the existence of longer waves, observing a period of first rising and then declining prices in data from 1790-1849 (Kleinknecht, 1987). By the 1920s, Joseph **Kitchin** (1923) had proposed shorter inventory cycles of 3-4 years, based on the study of British and American data going back to the 1890s, while others were studying much longer cyclical phases. William **Beveridge** (1921/22) identified 54 year periods in his spectral analysis of wheat prices, while Jacob **van Gelderen** (1913), Sam **de Wolff** (1929) and other Marxists were investigating the possibility that structural elements of capitalism were inherent causal factors in the patterns of long accelerations and decelerations of growth (Silverberg, 2003).

Indeed, modern long-wave scholars, if not economic textbooks, recognise that van Gelderen not only provided a rich statistical analysis, drawing on a range of time series, but that his theories were a key influence on Schumpeter and prefigured the discoveries of later researchers (Kleinknecht, 1987). However, **it was the Russian economist, Nikolai Kondratiev, whose work *The Major Economic Cycles (1925)* brought the notion of long waves to broader attention.** Working independently from the Dutch researchers, the conclusions that he drew from his detailed statistical analysis of growth rates, prices and other variables contradicted rather than supported Marxist expectations of the end of capitalism (Louca, 1999). Though well-received in the West, his theory of market-based 40-60 year growth periods, comprised of an upswing and downswing, implied the constant renewal of capitalism and cost him freedom in 1930 and his life in 1938, a victim of Stalin's Great Purge.

It was with Joseph Schumpeter's labelling of long waves 'Kondratiev Waves' (K-waves) in tribute after his death that the impression of the Russian as the founder of the long-wave theory was set. Yet, crucially, **Schumpeter saw a different causal mechanism to Kondratiev. He had been convinced for decades that it was innovation that drove and shaped growth in capitalism** (Schumpeter, 1911 [translated 1934]), **and concluded that cycles in economic performance, of whatever length, were therefore driven by innovations, too;** the longer the cycle, the more important and numerous the driving innovations must be. Published in 1939, his opus, *Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process*, presented the theory in 200 pages and then painstakingly went through the history of each of the first three long 'Kondratiev' waves of the industrial era, identifying all the technologies that drove them and incorporating the shorter cycles that shaped them: the 'Kitchins' inventory cycles and the 'Juglars' fixed investment cycles. The long Kondratiev waves would be driven by veritable technological revolutions. Note that although Schumpeter drew on the National Income data produced by Simon Kuznets (1930) (another believer in the role that technologies played in generating economic growth), he did not incorporate the 'Kuznets swing' into his theory at that time, although it is often included in the pattern.⁷

Following Kondratiev, Schumpeter saw the first wave driven by the Industrial Revolution in England (1787-1842); the second in the Age of Railways, the so-called 'bourgeois Kondratiev' (1843-1897); and the first half of the third wave developing from 1898 to 1913, in what he termed the 'neo-mercantilist' wave. His historical analysis highlights the role played by the state in protecting and supporting domestic industry in the US, Germany and most other European countries, particularly in contrast with the free-market British Empire, yet Schumpeter himself did not take away from that research a belief that government policy made a major difference in the success of those processes.

Instead, **he paid particular interest to the role of finance, which he saw as the necessary complement to the entrepreneur who, for Schumpeter, was the real driver of progress.** This continues as he attempts to grapple with the very recent past: analysing the years after the Great War, the crash of 1929 and the depression of the 1930s, he enters into a complicated argument in an attempt to disentangle the impact of market forces from those of state involvement in growth behaviour, especially when discussing Roosevelt's New Deal. It takes him 600 pages, and yet the border between the third wave and the fourth is not clear. The legacy of this gigantic effort was to show that, thanks to entrepreneurial innovation and investment, with financial support, markets naturally produce upswings in growth followed by downswings, to then recover with another

⁷ Kuznets' swing being a cycle of 15-25 years associated with infrastructural build-up and demographic shifts.

upswing. We shall return to the place of upswings and downswings in the periodisations of revolutions in Section Four on the neo-Schumpeterians.

Yet, **the empirical basis of Schumpeter's theory was almost immediately brought into question**, firstly by Kuznets (1940). While Kuznets agreed not only that technological innovation was crucial for economic growth, but that there were revolutionary moments in industries followed by a process of slow development, rapid expansion and then a levelling off, he did not believe that Schumpeter had empirically proven the existence of 50-year cycles, nor given evidence of the clustering of 'heroic innovations' in time.⁸

This question of statistical proof then became central to the dominant economic debate on the cyclical nature of capitalism: primarily econometric, and focused on K-waves (Mosekilde and Rasmussen, 1986; Devezas et al., 2005; Grinin et al., 2020). However, there have been interdisciplinarians, like Robert **Ayres** (1990), the physicist turned ecological economist and his peers from the International Institute for Applied Systems Analysis (IIASA); and, more recently, Markku **Wilenius** (2017), who have both incorporated K-wave analysis into a more complex, systems-analysis form of future forecasting.⁹ A number of those pursuing the topic in the latter half of the twentieth century did so in the Marxist tradition, such as **Kleinknecht** (op cit) and **Mandel** (1980); this shall be discussed further in Section 3.4. Some cycle scholars continued to focus on shorter periods, such as Angus **Maddison** (1982), who worked intensely on compiling world statistics of all the important variables in an attempt to test the various cyclical hypotheses. He developed his own periodisation of four distinct phases of capitalism: The 'liberal phase' 1820-1913 (divided into two periods in 1870); the 'beggar-thy neighbour' phase 1913 to 1950; the 'golden age' 1950-73; and from 1973 onwards 'the phase of blurred objectives'. He very explicitly defines the phases in terms of the policy context shaping investment, innovation and growth in the international economy, including policies towards unemployment, price stability, labour markets, trade and factor movements.

Key to understanding the frequent misuse of the term 'long waves' is that it specifically describes upswings and downswings in GDP and other economic variables, and is 'essentially a quantitative concept' (Gutiérrez-Barbarrusa, 2019) **but has been used to refer to periodisations in general.**¹⁰ Yet long wavers are those who start with the recognition of this pattern and work to explain it, often analysing discrete variables such as investment, new technologies, gold, competition from new entrants to explain these major fluctuations (Goldstein 1988). As shall be explained further in Section 3.7, the neo-Schumpeterians start with the recognition that technologies occur by revolutions, then work toward understanding how revolutions come together and how they propagate and are assimilated in the economy and society. Theories are frameworks that look for causality, and the starting point matters. So **while neo-Schumpeterians search for the causes of**

⁸ Later in his career, Kuznets (1955) identified what is subsequently known as the Kuznets curve: he observed inequality first increasing and then decreasing in the US between the 1920s and 1950s. Although this coincided with the patterns later identified by the neo-Schumpeterians, and was based on long-term data, Kuznets did not claim it was a regular cycle, nor did he connect it with his own earlier work.

⁹ Wilenius argues that we are now in sixth wave, one that coincides both with Schwab's fourth and the neo-Schumpeterian deployment of the fifth revolution: 'the age of intelligent, integrated technologies, helping to restore the balance between humans, technology and nature by radically improved material and energy efficiency and a wiser use of human potential.' (Wilenius 2017).

¹⁰ See, for example, Florida (1991) on 'The New Industrial Revolution', who includes the neo-Schumpeterians in 'long wave perspectives'; or Papenhausen's (2008) survey of 'long wave' literature.

technological revolutions, and then for what the revolutions cause in their diffusion, long wavers try to find the cause of long waves, often then needing to first show that the statistics prove that the waves indeed exist.

3.2 The historical view of technological revolutions

We find a very different point of view among the historians of technology and the managers and engineers, discussed in the next section. Their shared focus is on the technologies themselves and on their impact on employment, productivity, growth, organisations and/or culture. For them, statistics are mostly a descriptive tool, to give quantitative backing to what they observe, which is the actual set of technologies being introduced in the economy and the transformations they bring about. For them, what warrants the term ‘revolution’ is the radically new nature of the technologies involved in terms of changing crucial aspects of production and trading methods through new energy sources, materials or major new transport or communications networks. But when analysing the revolutionary changes, **there are differences between the economic historians of technology, who are concerned with the scientific origins or social forces that generate technical change, and the engineers who focus more on the consequences in the production sphere.**

The historians of technology

Economic historians have made a notable contribution to the scholarship on long waves and on the broader periodisations of technical/technological change (van Roon, 1981).¹¹ Among the major economic historians, a landmark was set by David **Landes**, whose seminal book *The Unbound Prometheus* (1969) follows in great depth the technological transformations which began in Britain at the end of the 18th century. Landes defines ‘industrial revolution’—in small letters— as the ‘shift from handicraft to manufacture [which] gives birth to a modern economy’ (Landes, 1969, p.1). The expression with capitals is for him the process that ‘began in England in the eighteenth century, spread therefrom in unequal fashion ... and transformed in the span of scarce two lifetimes the life of Western man, the nature of his society, and his relationship to the other peoples of the world.’ (Landes, op. cit.). Thus, although he distinguishes in his chronology the late 18th century to 1873 from the periods of 1873 to WWI, the interwar years and, lastly, from 1945 to the time of his writing in the 1960s, he does not label these epochs as separate revolutions. Yet, his focus and dating have allowed subsequent authors to distinguish the periods as distinct upheavals in technology. His work is perhaps the most all-encompassing in terms of describing the technologies and following the multiple direct consequences of technical change on workers and work organisation, on production, trade and even politics.

Joel **Mokyr** has been highly influential across academic and popular discourse, both for his painstaking documentation of the technologies not only of capitalism but also its precedents his

¹¹ Note that within the innovation literature technical and technological have different meanings. ‘Technological change’ refers to change across an entire range, whether that be of a system or a revolution, and as such has quite a specific use; ‘technical’ can have both a narrower and broader application, such as ‘company X is investing in technical change’; ‘the printing industry is in the midst of deep technical change’; or ‘historians studying technical change through the ages’. In the popular debate, however, ‘technological’ has come to cover all areas, while still often being interpreted in a very limited sense, to mean specifically new and hi-tech gadgetry. We use the conventions of the innovation literature in this paper.

detailed analyses of the origins of the Industrial Revolution (Mokyr, 1999). Carefully reviewing the data and theories of his contemporaries, scholars of the period such as Nick Crafts and Patrick O'Brien, he argues for the role of the Enlightenment focus on scientific and tacit knowledge, which he sees as generating the 'culture of growth' of the modern economy (Mokyr, 2016). With that, **he incorporates into the process the cultural dimension, which also has socio-political implications.** Of particular interest are not only his study of the motives for technical change, but also the sources of resistance to it. Mokyr distinguishes two major revolutions in the industrial period: the first in England in the 18th century and the second, beginning in the 1870s, spreading across Europe, North America and beyond. It is difficult to deny the momentous changes brought by technology from the 1870s and the so-called 'great depression', in fact a great deflation, that ensued in those years. The massive price reductions were driven by both productivity increases in manufacturing and the rapid steamships that brought much cheaper food and materials from the Southern hemisphere (much of it under colonial rule) and the new fields in America.

The (socio)-economic historians

Also in this group are those economists whose analyses emphasise the social consequences of technological change. Whilst not economic historians per se, they take the long-term view and analyse the historical impact of technical change on ways of life and employment. One prominent example is **Robert Gordon**, whose 2012 NBER Working Paper predicted the end – or at least significant slowdown – of American economic growth (Gordon, 2012; 2016; and see, for example, Porter, 2016), Gordon frames his argument around the quality of the daily lives of Americans and to what degree technology has brought positive change: in terms of lower prices (resulting from productivity increases), more and better products and less arduous jobs that free up time and reduce hard toil at work and in the home.¹² His work is almost entirely focused on the U.S. case.

Gordon's periodisation is complex, initially referring to many separate 'revolutions' by sector – in transportation, housing, modern conveniences, finance and so on. He then groups these into three major 'industrial revolutions'. The first begins in England in 1750, taking the entire 19th century to diffuse. The second starts around 1870, taking until the 1970s to propagate, while the third, the information revolution, begins in 1960 and still spreading across the world. Gordon essentially views a revolution as a cluster of major inventions that then take decades from their inception to make the transformations that increase productivity and transform lives.

He distinguishes 1920-1970 as the time when the innovations of his second revolution (electricity, running water, automobiles, etc.) bore fruit, leading to the fastest growth experienced by the US economy and the most profound improvements in standards of living. Yet he sees this as a one-time feat, the 'low-hanging fruit of modern history' proposed by his contemporary, Tyler **Cowen** (2011), another economist regularly cited in the public discourse around growth in the past decade. **Gordon's basic contention is that the information revolution is a minor one compared to the previous transformation; he considers it without great promise either in productivity or in living**

¹² Note that Gordon, like the majority of authors mentioned here, may not see technological progress as continuous but do, typically, take the positivist approach and assume that it is generally desirable, even if it produces bads that need to be rectified by future generations. Thus Gordon talks of the increasing need to address environmental damage and sustainability as a 'headwind' to future economic growth (a view the authors of this paper do not hold); he does not, for example, consider the loss of indigenous lifestyles and knowledge as a loss of 'technology'.

standards. Confronted by the 'headwinds' of inequality, poor education, demography, ICT-driven innovation, environmental restrictions and rising fiscal pressures, he sees the United States inevitably heading for massive unemployment and secular stagnation.

While Gordon concentrates on the impact of technology on the standards of living, Carl Benedikt **Frey focuses on the impact of technological change on work, and the ensuing social and political consequence.** Analysing technological unemployment from preindustrial times to the potential of automation to change employment patterns into the future, Frey's 2019 book centres on a comparison of the disruption and inequality wrought by the Industrial Revolution to the political and economic polarisation of today. This follows a highly influential working paper, co-authored with Michael **Osborne**, which presented an in-depth survey of the likelihood of specific jobs to be displaced by artificial intelligence, robotics or other automation technologies (Frey and Osborne, 2013). Used by the Bank of England (Haldane 2015), the World Bank (2016) and others for future forecasting, that work has been cited regularly – and often inaccurately pessimistically – in the '**robots are taking our jobs**' narrative of current and future technological change in the press (see for example BBC, 2015; Ford, 2015).

Frey's periodisation is not very precise, in part because that is not his focus. **He refers to mechanisation, the steam engine, electricity, mass production, computers, robotics and artificial intelligence not as sets of interrelated systems of innovation but as equivalent processes replacing machines for labour,** often making parallels from one period to another. Revolutions matter in as much as they affect employment, which in turn results in social inequality or betterment and may influence culture and other aspects of life. **Governments are important when they forbid or favour job displacing machinery, but not as possible shapers of the direction of technology overall.** Neither does he look in detail at the role of public training or education. So despite an emphasis on job and skills destruction, and the recognition that this has, and does, cause serious political and economic consequences, the 2013 analysis does not end with a call to policy makers, but instead observes that 'for workers to win the race [...] they will have to acquire creative and social skills.' (Frey and Osborne, op.cit., p.48).

The great importance of Frey and Osborne's work resides in the exhaustive analysis of the potential impact of each technology and its application on each type of job and skill. In contrast with Schwab, they do not go deeply into the positive or negative social consequences of each change. It is, however, useful that Frey does frequently make parallels with previous historical experiences of dislocation, displacement, replacement or other impacts, where technologies have affected working numbers, conditions, skills or requirements.

3.3 The business and engineering perspective

Having previously been a niche academic pursuit, the work of economic historians on the evolution and impact of technical change is now coming to the fore, with a broader appeal to society at large. The momentous transformations of the Information Revolution have put the topic on the table for everybody, from managers, policy makers and politicians, to labour leaders and young students deciding on a career. Technology is no longer a terrain for specialists; we are all involved and affected, for better or for worse. **And those business leaders, entrepreneurs, managers, consultants, and all those others focused on production itself as a transformative process – who, in**

our categorisation, we have dubbed ‘the engineers’ – can no longer see their work as merely technical. Whilst previously unconcerned with either the origins of the technologies and their social demand for solving problems, nor focused on the political implications or responses to the changes the new technologies effect, they are increasingly recognising its impact on people and on the planet.

It is in that context that the issue of ‘how many and which revolutions’ is now being discussed and that both predictions and recommendations are being advanced. **It is then the concern of engineers and business leaders to understand where technology may be taking us and whether we can do something to shape it.**

Gordon’s pessimistic outlook is confronted by the optimism of MIT’s Erik **Brynjolfsson** and Andrew **McAfee**; indeed, much has been made of the ‘techno-optimists vs pessimists’ debate over the past decade.¹³ The primary contention of Brynjolfsson and McAfee’s popular second book on the implications of digital technologies, *The Second Machine Age* (2014), is that while the machines of the Industrial Revolution replaced physical human (and animal) power, the Information Revolution is and will be about replacing mental power. For them, these are the only two revolutions. They do not date the latter from the microprocessor in 1971 or from the government handover of the internet to the private sector in the mid-1990s, but from sometime in the 2010s, when artificial intelligence was already clearly showing its promise to replace highly skilled mental work – in driverless cars, geological data interpretation, winning at chess and general knowledge competitions or directing robots. For Brynjolfsson and McAfee, what technologies can do, they will do. **Their analysis concentrates on the consequences of the initial effects that emerge, assuming that these are here to stay and advocating that society – and policy – must accommodate these effects, finding ways of softening the blow of the negative consequences while taking advantage of the positive ones.** In fact, their approach is so deterministic in this sense that their recommendations do not include regulation, social welfare measures or any other aspect that could hinder unfettered market forces or truly protect its victims.

Continuing in this vein, McAfee (2019) claims – with the support of selected data – that the market is already reducing materials and energy consumption significantly and will continue to do so. Therefore, **he limits his recommendations regarding the environment to ‘nudges’ rather than policies or other actions that would drastically modify the playing field in favour of green innovation and investment.**

Thus **although taking completely opposite interpretations of the power of information technologies, both Gordon and the MIT team see society as essentially powerless in shaping the outcome of the ICT revolution for the better; rather, they see technology marching forth, generating increasing distance between ‘winners’ and ‘losers’ and thus driving up inequality, with only marginal social and political interventions preferred to soften these impacts.**

¹³ See the debate staged at TED 2013 (Brynjolfsson and Gordon, 2013), and all the press coverage that resulted; and *The Economist*, 2016, for but two of the earlier mainstream commentaries. The debate continues to be applied across society; see for example Ganesh 2021 on techno-pessimism in contemporary literature.

Klaus Schwab's stakeholder view: facing the consequences to improve the world

Although Klaus Schwab's interpretation of the power of current technologies coincides with the Brynjolfsson and McAfee vision of the ICT revolution, he expresses a much clearer concern about its effects and makes an active call to make sure that all stakeholders participate in recognising the risks and promises of the technologies and in shaping their direction (Schwab, 2016). This is perhaps not so surprising given the German context (as opposed to the US focus of Gordon and Brynjolfsson and McAfee), in a country with a long tradition of association and negotiation among stakeholders, within and between firms, and with the participation of banks and the local or national government as well as workers' representatives on company boards (McCraw, 1998). Founder and executive chairman of the World Economic Forum (WEF), Schwab can be credited for popularising the term Industrie/y 4.0, originally coined at the turn of the last decade to refer to the digitisation of machinery with the goal of enhancing German competitiveness, which has now become practically ubiquitous in academia, policy-making and popular parlance to describe the current revolutionary changes (see discussion and data in the Appendix).

Indeed, that term, and the notion that we are now in a Fourth Industrial Revolution (ibid), has now all but crowded out other periodisations of technological change, despite very little critical interrogation of the empirical or theoretical grounding of the concept (see the Appendix for further discussion and references). Schwab himself goes into more detail than most who merely accept this notion at face value. In his popular WEF pamphlet turned book, he first locates the current transformation in a historical context by referring to the agrarian revolution and identifying four historical industrial revolutions to date. He then follows Brynjolfsson and McAfee in grouping the first three of these as the transition 'from muscle power to mechanical power' and the current fourth as when 'enhanced cognitive power is augmenting human production' (ibid p.9).

His dating coincides with most authors in locating the first of the industrial revolutions towards the end of the 18th century, although in 1784, slightly later than others. That revolution, according to Schwab, consisted of mechanical production equipment moved by steam and waterpower. As to the second, he again coincides with most authors when dating it from 1870, but bundles together components that develop earlier – such as steel and electricity – with those that develop much later, notably Fordist mass production. In this second period, he also includes the 'division of labour' (Smith 1776) while not mentioning the automobile – perhaps because, still **taking his lead from industry, he is focused on that which affects production methods, rather than on what is actually produced and the way in which that substantially changes ways of life.**

Indeed, although he defines revolutions as 'when new technologies and novel ways of perceiving the world trigger a profound change in economic systems and social structures', this focus on the transformation of production methods is likely to be the reason for his choice of the components of each revolution (op. cit.). For instance, although the car, radio, plastics and home electrical appliances profoundly affected ways of life via decreasing prices, thanks to the Fordist assembly line introduced in 1913, he does not see them as a revolution. Rather, he groups together the 100 years between the shift from iron to steel in the 1870s to the introduction of computers, which he dates to 1969.¹⁴

¹⁴ Perhaps because the portable operating system UNIX was introduced in that year, making computerisation of industry much easier.

His third revolution relates to electronics, IT and automated production, beginning in 1969. And finally, the fourth, which is both the object of the book and has been a central theme at Davos (World Economic Forum, 2016), is what he calls the Age of Cyber-Physical Systems. Artificial intelligence, smart connected machine systems and robotics take central stage, but he also includes bio and nanotechnology as well as renewable energy (see Figure 1).

Figure 1. The Schwab (WEF) sequence of industrial revolutions

Revolution	Year	Information
1	1784	Steam, water, mechanical production equipment
2	1870	Division of labour, electricity, mass production
3	1969	Electronics, IT, automated production
4	?	Cyber-physical systems

Source: Davis, 2016.

As noted in the figure published by the World Economic Forum, there is no initial date yet for the fourth revolution (neither does Schwab provide it in his book). This seems to imply that the transformation must be already under way for it to merit the term revolution and not just the availability and early adoption of the technologies that will drive it. We will see below that this marks a difference with the neo-Schumpeterians.

Having centred attention on the production process, Schwab’s first concern is the displacement of labour and skills and how to combat this. Here, he goes much further than Brynjolfsson and McAfee, who seem to think that some mild measures to make the market work more smoothly would solve the main negative consequences (ibid, chapter 13). Instead, he takes an approach similar to that of Frey and Osborne, but rather than starting with current jobs and extrapolating their future standing, Schwab looks at each of the potential technologies and its applications, from there identifying the jobs or skills that could be displaced. His analysis is based on a wide-ranging survey among 800 business executives asking about the likelihood of diffusion of certain technological possibilities and the speed at which tipping points would be reached (ibid, Appendix; World Economic Forum, 2015).

In the original formulation, Schwab made it clear that the shaping of technologies for the better was the job of all the stakeholders, but he saw the dangers of each separate technology as defining goals in each case. In his latest work (with Malleret, 2020), he defines overarching directions for the required changes. **They thus go much further into the possible and desirable socio-political shaping of the current advanced technologies, proposing various leverage points for ‘resetting’ the socio-economic landscape following the COVID-19 pandemic, and paying particular attention to social and environmental sustainability.**

Since Schwab’s view of the current technological opportunities and threats has been generally accepted (see the Appendix for data) – in fact, our Beyond 4.0 project is a response to that view¹⁵

¹⁵ See the Beyond 4.0 Guidance paper, D2.1. (Warhurst et al., 2019).

– we will analyse its strengths and shortcomings in the final section, when we discuss the consequences of adopting one or another interpretation of technological revolutions in general and of the current one in particular.

3.4 The Neo-Marxists

Given the importance given by Marx and Engels to the ‘forces of production’ as shaping the organisation of society (the ‘mode of production’), it is not surprising that those following the Marxist tradition should also look at technology to explain major transitions – especially in analysing changes in the political economy shaping each period. For those in this school, there is also an impetus to understand and update their own theoretical roots, given that Kondratiev seems to have – thus far at least – been proven right in his prediction that the cyclical patterns of capitalism have enabled it to survive the contradictions that Marx believed should have brought its demise.

L’École de la Régulation

The ‘Regulation’ school – notably Michel **Aglietta**, Alain **Lipietz** and Robert **Boyer** – sets out to broaden and update the Marxist understanding of capitalist accumulation and of the confrontation between capital and labour. It sees capitalism as a succession of modes of regulation associated with different conditions of accumulation, each reaching a crisis that forces its replacement (Aglietta, 1979; Lipietz, 1986). The mode of regulation and the legal framework are modified each time to enable the successful functioning of more powerful forms of capital. Such a stabilising context includes the functioning of markets – in terms of the main forms of competition – and capital-labour relations, including the principal forms of work organisation and determination of wages.

Within this framework, scholars recognise four modes of regulation with a different regime of accumulation, starting in 1850 (Hein et al., 2014). The first of the ‘growth regimes’ is the ‘extensive mode’ of high competition, replaced, from about 1900, by the ‘intensive mode’: high productivity via Taylorism and the growing concentration of production. Boyer (2000) actually sees these as two periods of essentially the same ‘competition’ mode. Then, from 1930, this switches to a ‘monopolist mode’, with Fordist high productivity and mass consumption. The current mode is generally referred to as ‘financialised’, or a variant of that term (ibid).

In each case, the forms of organisation of work are seen to respond to the nature of the new technology, and the capacity of those technologies to increase productivity. This way of organising is accompanied by a regulatory framework at the national level, which creates the conditions to maximise productivity and profitability. Although there are many schools stemming from the original French group, including Bob **Jessop** in the UK, Jamie **Peck** in Canada, and Christoph **Scherrer** in Germany, each taking somewhat different directions, **the essential tenet is that capitalism modifies conditions each time that the previous set no longer provides an optimum context for capital accumulation.**

Social structures of accumulation

In a similar vein, but here very much focused on the changing nature of capitalism, is the ambitious periodisation of **David Gordon** (1980) (brother of Robert Gordon discussed above), further developed by Samuel **Bowles**, Richard **Edwards** and Frank **Roosevelt** (2005), a group of American economists trying to unravel the logic of the system and its metamorphoses. Their periodisation, which is very similar to that of the Regulation scholars, represents what they see as deep changes in capitalism as a form of wealth accumulation: Competitive Capitalism, from 1860-1898; Corporate or Monopoly Capitalism, 1898-1939; Regulated (post-war) Capitalism, from 1939-1982; and finally Transnational or Global Neoliberal Capitalism.

Their view of technology focuses on the forms of competition and the sources of profit and therefore of capital accumulation by the more powerful firms at the centre of the system in each period. As to technical change, although they do not see it as the source of transformation of the system from one stage to another, nor refer to technological revolutions, they do keep technology centrally in mind.

Hobsbawm: A prolific interdisciplinary historian

The historian Eric **Hobsbawm**'s four 'Ages' books cover the history of capitalism and can be read as an in-depth description of the economic and socio-political developments that occurred with the spread of each new technological revolution. His Age of Revolution, spanning from 1789 to 1848, marks the French Revolution as the political transformation and the Industrial Revolution as the economic one. The Age of Capital covers the heady industrialisation and urbanisation period of 1848-1875, the epoch usually referred to as 'the Victorian boom'. The Age of Empire, from 1875 to 1914, details the period of the 'Pax Britannica' until the eruption of World War I, during which time the US and Germany forged ahead of Britain in developmental terms and the countries of the Southern hemisphere made a leap in development joining the agriculture and mining markets – the first globalisation. And, finally, The Age of Extremes covers 1914 to 1991, the years shaped by mass production, oil and the automobile. Throughout, Hobsbawm details and analyses politics, economics, culture, social movements and ideologies, as well as scientific and technological advances. As if that were not already a Herculean task, he also endeavours to do this for the entire globe, in an early attempt to counter the European bias. **His periodisation criteria are more about changes in power structures than in technology, but they take into account all aspects of each transformation and are invaluable in understanding the patterns of the paradigm shifts brought about by each technological transformation.**

3.5 Innovation-centred: between Marx and Schumpeter

Gerhard **Mensch** (1975) attracted attention and stirred up debate during the resurgence of interest in long waves, business cycles and revolutions of the late 1970s and 1980s (see Appendix), which can be attributed to the double-digit unemployment and inflation that followed the Post War boom. Mensch's interest lay in explaining the frequency of innovations (defined as the successful commercial introduction of novelties, as distinct from inventions). **He held that innovations came**

in bunches, clustered in recessionary periods, and his ideas inspired Marxist long wave scholars such as Mandel, as well as the Systems Dynamics group at MIT (Graham and Senge, 1980).

Whilst Mensch's work concentrated on US statistics of patents and innovations, Andrew Tylecote, by contrast, analysed each of the technological revolutions in their components and their diffusion, together with their social consequences. Though with a Marxist background, like Mensch, in the scope of his work he can be considered a neo-Schumpeterian. His theory of long waves (Tylecote, 1992) is a critical combination of concepts from the French Regulation School discussed above together with Perez' (1983) initial neo-Schumpeterian formulation of successive new 'technological styles,' confronting a mismatch with the socio-institutional framework; and George Modelski's (1987) 'cycles of world political leadership'. However, **Tylecote's resulting formulation**, an enriched fusion of those elements, **leads to a different dating from that of the neo-Schumpeterians**. Essentially, **he respects the tendency of long wavers (and, partly, of Schumpeter), to periodise the repetitive pattern by beginning with the upswing in the economy and ending with the downswing**.

This is a key distinction to understand when looking at all those who study technological revolutions. The irruption and diffusion of each new technological paradigm across the socio-economic spectrum are better understood by marking the beginning of the pattern with the appearance and early, niche, diffusion of each new set of technologies, and ending it at economic maturity, when stagnation has started and the new revolution that will replace those once novel technologies is already apparent. **Thus Tylecote's revolutions** begin in 1780, 1850, 1896 and 1945, which, except for the first Industrial revolution, **are almost exactly the beginnings of what Perez sees as the golden ages that start midway along with the propagation of each revolution**.

Tylecote's work was lauded as the first attempt at examining the revised neo-Schumpeterian hypotheses, through the historical record, to identify not only the various components of each successive technological revolution but also their cultural, social and political consequences.

3.6 Technological transitions studied at the meso-level

Within the wide interdisciplinary field that is usually called Science and Technology Studies (STS), there are various schools of thought that look at the interaction between technology and society with the aim of understanding technology-related structural change, identifying the way that technical change processes take place in specific sectors or industries. The aim of some is to question technological determinism and highlight the potential for social shaping; the goal of others is to develop a theory of socio-technical transitions in general. **Their focus is understanding the forces at play either in the construction of organisations or in their transformation**. They often use historical experience as their object of study, recognising that recurring processes in the past can shed light on both current and future transitions. However, STS scholars generally stay at the sectoral or meso-level and seldom extend their analysis to the notion of 'revolutions', with the exception of the Deep Transitions School discussed below. Their work is nevertheless an important source for understanding the impact of technical change and how it is socially shaped.

The socio-technical approach

Early attempts at understanding the social processes of transformation and transition under pressure from technology were made by several groups of scholars from different disciplines – sociology, psychology, anthropology, management, psychology and beyond – that together can be recognised as socio-technical schools (Bijker and Law, 1992). The aim of these scholars has been to reject notions of technological determinism, arguing instead that it is possible to shape the outcome for the better, particularly in terms of employees' wellbeing in the workplace (Trist, 1981). In other words, **they see socio-technical systems as socio-politically shaped**. A broader notion of socio-technical systems as stable structures involving focusing on the interdependence of social and technological factors in shaping organisations was developed by the Tavistock School, which has been highly influential in the development of the current roster of scholars studying the social shaping of technology at the sector, industry and individual company level (Trist and Murray, 1993; Griffith and Dougherty, 2001). The socio-technical approach is clearly interdisciplinary and can be seen as strengthening the capacity to formulate appropriate policies for the more socially sustainable use of technologies.

The Dutch Transitions School

Combining socio-technical ideas with notions from evolutionary economics, the Dutch Transitions school or 'multilevel perspective' focuses on the process of change from one socio-technical regime to another and has direct application to the study of technological revolutions. **They not only look at the emergence of radical innovations in 'niches', but also at the conditions under which these innovations can diffuse more widely and replace the existing regime**. These conditions are thought to include external ('landscape') pressures, endogenous problems or tensions in existing regimes (due to reaching maturity and limits) and increasing momentum of niche-innovations (due to learning processes, cost reductions and expanding actor coalitions) (Rip and Kemp, 1998; Geels, 2002). Furthermore, they recognize the intricate interaction between technology and behavioural choice (by managers, employees, and works councils) as a complex process. They observe the development of 'integral design rules' for the joint optimisation of the social and technical system, in which change occurs due to a normative drive to balance of managerial and worker interests in terms of flexibility, quantity and quality of goals, including products, profit, and job quality (Kuipers et al., 2020; De Sitter et al., 1997; Mohr and Van Amelsvoort, 2016). In a Neo-Schumpeterian fashion these authors see room for strategic choice, managerial choice to guide technology development and implementation to arrive at the 'best' results. While this school does not refer directly to technological revolutions as such, they do include a third level, above the niche and regime ones, that they call the 'landscape', representing all the other conditions and transformations that conform to the context for the direction taken by the niches and the regime.

Deep Transitions project

There is, however, an offshoot of that school, the Deep Transitions project, that does examine long term historical experience, merging the neo-Schumpeterian notion of great surges (to be discussed below) with the transitions model. Johan **Schot** and his team posit **the notion of Deep Transitions**,

of which the Industrial Revolution would have been the first and the present ICT revolution the second (Schot and Kanger, 2018; Kanger and Schot, 2019). In their view, the evolution of technology has gone through successive energy-intensive mass-production systems within the first deep transition, – i.e. encompassing what for others are several separate revolutions. They contrast the fossil fuel-based mass production period beginning in the 1780s with the green transformation that would be emerging as a deep transition in the 21st century.¹⁶

The Dutch tradition does hold two different directions in change, one that could be interpreted as more deterministic in that market demands are posited as shapers of internal organisational change. However, the other relies more on ad hoc decisions taken by managers in their particular temporal context, and recognises that change is not necessarily progressive; new managers may revert to old practices due to short-sightedness, for example. One can say that the most important contribution of the socio-technical and transition schools is the provision of an interdisciplinary theory of social change that has application at various levels, micro-, meso- and, potentially, at the macro-level of technological revolutions. **In terms of the analysis in this paper, they contribute to the notion of social shaping of technology, providing case study research, conceptual development and theoretical frameworks to explain the absorption of technological change.**

3.7 The Neo-Schumpeterians: the mutual shaping of technology and society

The neo-Schumpeterians, or evolutionary economists,¹⁷ see the complex systems of biology as a better model for the functioning of the economy than the discrete models of physics, as have been emulated by orthodox economists. **They adopt the core Schumpeterian belief of innovation as the source of dynamism and growth in the economy, but distance themselves from Schumpeter's notion of the market as the sole determinant of economic behaviour and as a guarantor of eventually reaching equilibrium.**

As to technological revolutions, they hold on to the notion of the clustering of interrelated innovations that have a massive transformative impact on the economy through a process of 'creative destruction', but do not accept Schumpeter's view that this takes the form of major upswings and downswings in macro-economic aggregates such as GDP. They hold that such macro-data conceal much more than they reveal, a belief around which there is a burgeoning consensus (Mazzucato, 2018). In addition, and **in contrast with Schumpeter, they give a key role to government and society in the shaping of technical change and innovation, and analyse the interrelations between the techno-economic sphere and the socio-political one.**

In the innovation sphere, the first neo-Schumpeterian to specifically engage in a study of the social impact of technological revolutions was Christopher **Freeman**. Together with Jon **Clark** and Luc

¹⁶ This is not dissimilar to the views of Jeremy Rifkin, who sees the 'lateral power' of the networked present allowing green energy to replace the dominance of oil in a 'third industrial revolution' (Rifkin, 2011); his work was very influential within EU and UN governance circles at the start of the last decade. John Mathews is another proponent of the transformative power of renewable energy; he, however, puts the switch to green as the sixth revolution. (Mathews, 2013).

¹⁷ For an external discussion of whether the two terms are interchangeable, and a survey of the field that includes views of the approach/es which differ to the principal investigator's, see Martin (2012).

Soete, he analysed the historical role of the impact of major technical changes on un/employment (Freeman, Clark, and Soete, 1982). Carlota **Perez**, principal investigator of this Beyond 4.0 work package, began a collaboration with Freeman in the 1980s, **developing the notion that the disruption caused by Schumpeterian 'creative destruction' in each technological revolution changed the paradigm guiding all innovators, producing a mismatch between the emerging economy and the old policy context** (Perez, 1983; Freeman and Perez, 1988).

Two influential works from this partnership were published at the turn of the century, and perhaps can be considered the last major boom in interest in technological revolutions before the 'Industry 4.0' concept explosion (see Appendix for more details). Freeman and Francisco **Louçã** (2001) argued for the existence of long waves as processes of major transformation, discussed the theories of Kondratiev and Schumpeter in-depth, and identified and analysed in detail each of the five revolutions since the 'Industrial' revolution in England at the end of the 18th century. Perez (2002) re-introduced Schumpeter's view of the key role of finance in innovation and analysed the changing interactions between production and financial capital in relation to technological revolutions. This work resulted in **the final abandonment of Schumpeterian upswings and downswings in GDP to concentrate on the regular patterns of propagation of technologies across the economy and society and how they are, in turn, socially and politically shaped**. These patterns needed a name to distinguish them from the upswings and downswings, the cycles, long waves and k-waves that are still so often used interchangeably; in the Perez nomenclature, they are known as 'great surges of development', complete with distinct phases that shall be discussed below.

Table 1. Examples of different periodisations of industrial revolutions

	1700	1780	1820	1830	1850	1870	1913	1940	1950	1970	1995	2004 >
Landes		1 st industrial revolution (The Industrial Revolution): late 1700s				2 nd revolution: late 1870s		3 rd industrial revolution: 1940s to present				
Mokyr		1 st industrial revolution: first phase 1820-1850		1 st rev.: second phase 1850-1870		2 nd rev: 1870-1914				A 3 rd industrial revolution? 1970-present		
Kondratiev and Schumpeter		1 st wave: Industrial Revolution 1787-1842			2 nd wave: Bourgeois wave 1843-1897		3 rd wave: neo-mercantilist wave 1898 onwards					
Maddison		Capitalism: phase 1 1820-1870			Phase 2: the liberal order 1870-1913		Phase 3 1913-1950		Phase 4: the Golden Age 1950-1973	Phase 5: neoliberal order 1973-1994	phase 6? 1995-present	
Rifkin	1 st industrial revolution: 1700-1850			2 nd industrial revolution: 1850-1913				3 rd industrial revolution: 1950 - present				
Gordon	1 st industrial revolution: 1750-1830			2 nd industrial revolution: 1870-1972			3 rd industrial revolution: 1972 to present					
				Diffusion of impacts of 1 st rev		Main benefits of 2 nd rev: 1900-1929	Additional benefits of 2 nd rev to smaller towns and rural areas: 1929-70		Rapid growth 1972-96	Climax 1996-2004	Slowdown 2004-12	
Brynjolfsson and McAfee	First Machine Age: late 1700s to 2000										Second Machine Age: 2000 >	
Schwab	1 st industrial revolution: 1784-1870				2 nd industrial revolution: 1870-1969				3 rd industrial revolution: 1969 - ? and 4 th industrial revolution: now?			
Perez	Industrial revolution: 1771-1828		Age of Steam and Railways: 1829-1874		Age of Steel, Electricity and Heavy Engineering: 1875-1907		Age of Oil, the Automobile and Mass Production: 1908-1970		Age of Information and Telecommunications: 1971 >			

4. Defining technological revolutions from a Neo-Schumpeterian perspective

4.1 The structure of technological revolutions

Neo-Schumpeterian thinking distinguishes radical innovations from incremental ones, the latter of which are merely improvements to existing ones. **We define revolutionary technologies as major radical innovations – e.g. computers – with multiple uses across many sectors and see technology systems as strongly inter-related groups of radical innovations – e.g. computers and software – and finally technological revolutions as the creative gales of destruction that encompass many technology systems and spread across the whole economy.**

For each revolution, we can identify a major infrastructure that significantly widens markets and reduces costs of transport and communications, an all-pervasive input – a source of energy or a material – that is reliably cheap and becoming cheaper, and a set of major inter-related innovations in production methods and in products or services. Together, they lead in their early use to the construction of a techno-economic paradigm that becomes the ‘common sense’ logic for innovation, investment and consumption, in order to make the best use of the revolution and its transformative potential. Table 2 shows the components of each of the five revolutions to date.

Table 2. The industries, infrastructures and paradigms of the five technological revolutions

Technological revolution	New technologies and new or redefined industries	New or redefined infrastructures	Techno-economic paradigm ‘Common-sense’ innovation principles
FIRST: From 1771 The ‘Industrial Revolution’ Britain	Mechanised cotton industry Wrought iron Machinery	Canals and waterways Turnpike roads Water power (highly improved water wheels)	Factory production; division of labour; efficiency Mechanisation Productivity/ time keeping and time-saving Fluidity of movement (as ideal for machines with water-power, for transport through canals and other waterways and for human work on

Technological revolution	New technologies and new or redefined industries	New or redefined infrastructures	Techno-economic paradigm 'Common-sense' innovation principles
			products from task to task) Local networks
SECOND: From 1829 Age of Steam and Railways In Britain and spreading to Continent and USA	Steam engines and machinery (made in iron; fueled by coal) Iron and coal mining (now playing a central role in growth) Railway construction Rolling stock production Steam power for many industries (including textiles)	Railways (Use of steam engine) Universal postal service Telegraph (mainly nationally along railway lines) Great ports, great depots and worldwide sailing ships City gas	Economies of agglomeration/ Industrial cities/ National markets Power centres with national networks: decentralised centralisation Scale as progress Standard parts/ machine-made machines Energy where needed (steam) Interdependent movement (of machines and of means of transport) Free markets as the ideal context
THIRD: From 1875 Age of Steel, Electricity and Heavy Engineering USA and Germany overtaking Britain	Cheap steel (especially Bessemer) Full development of the steam engine for steel ships Heavy chemistry and civil engineering Electrical equipment industry Copper and cables Canned and bottled food Paper and packaging	Worldwide shipping in rapid steel steamships (use of Suez Canal) Worldwide railways (use of cheap steel rails and bolts in standard sizes). Great bridges and tunnels Worldwide Telegraph Telephone (mainly nationally) Electrical networks (for illumination and industrial use)	Giant structures (steel) Economies of scale of plant/ vertical integration Distributed power for industry (electricity) Science as a productive force Worldwide networks and empires (including cartels) Universal standardisation Cost accounting for control and efficiency Great scale for world market power/ 'small' is successful, if local

Technological revolution	New technologies and new or redefined industries	New or redefined infrastructures	Techno-economic paradigm 'Common-sense' innovation principles
<p>FOURTH: From 1908 Age of Oil, the Automobile and Mass Production In the USA and spreading to Europe</p>	<p>Mass-produced automobiles Cheap oil and oil fuels Petrochemicals (synthetics) Internal combustion engine for automobiles, transport, tractors, aeroplanes, war tanks and electricity Home electrical appliances Refrigerated and frozen foods</p>	<p>Networks of roads, highways, ports and airports Networks of oil ducts Universal electricity (industry and homes) Worldwide analogue telecommunications (telephone, telex and cablegram) wire and wireless</p>	<p>Mass production/mass markets Economies of scale (product and market volume)/ horizontal integration Standardisation of products Energy intensity (oil-based) Synthetic materials Functional specialisation/ hierarchical pyramids Centralisation/ metropolitan centers–suburbanisation National powers, world agreements and confrontations</p>
<p>FIFTH: From 1971 Age of Information and Telecommunications In the USA, spreading to Europe and Asia</p>	<p>The information revolution: Cheap microelectronics. Computers, software Telecommunications Control instruments Computer-aided biotechnology and new materials Artificial intelligence, Robotics, Internet of Things</p>	<p>World digital telecommunications (cable, fibre optics, radio and satellite) Internet/ Electronic mail and other e-services Multiple sources, flexible use, electricity networks High-speed physical transport links (by land, air and water)</p>	<p>Information-intensity (microelectronics-based ICT) Decentralised integration/ network structures Platforms Knowledge as capital / intangible value-added Data as raw material Heterogeneity, diversity, adaptability Segmentation of markets/ proliferation of niches Economies of scope and specialisation combined with scale Globalisation/ interaction between the global and the local</p>

Technological revolution	New technologies and new or redefined industries	New or redefined infrastructures	Techno-economic paradigm 'Common-sense' innovation principles
			Inward and outward cooperation/ clusters Instant contact and action/instant global communications

Source: Perez (2002) Ch. 2, Tables 2.2 and 2.3 (adapted and updated by the author)

4.2 The regular pattern of diffusion

An extremely important element of the neo-Schumpeterian analysis of technological revolutions is **the identification of a regular pattern in their propagation in terms of the relationship between financial capital, production capital and the State.**

To begin with, a technological revolution only comes together and irrupts in the economic space when the previous revolution has exhausted its potential for increasing productivity, markets and new products along well-trodden paths. This initial Installation Period is a huge experiment in which the new technologies replace or displace established industries, destroy jobs and skills on a huge scale and profoundly affect sectors, regions and countries. These turbulent times are led by financial capital, resulting in one or more major bubbles followed by what comes to be seen as an inevitable crash/es. The recession that ensues reveals all the inequalities that have resulted, and brings forth resentment, which serves as fertile ground for populism, as cause for divisions in existing political parties and the rise of new movements. However, this moment in time also reveals enormous technological potential which has been generating in niches, is now well understood, and which can be guided in socially beneficial directions. Hence, this recessionary period becomes the Turning Point towards what, in the past, have been the golden ages of each great surge of development.

Production capital takes the reins from finance in a Deployment Period – that is, if and when sufficient political forces are able to generate a positive-sum game between business and society. This period has, in previous revolutions, reversed inequity and stimulated innovation and investment in directions that have benefitted society while being profitable for business. Such are the golden ages, led by production and supported and guided by the state. The historical record is shown in Figure 2; we discuss the socio-economic impact of each surge further in section 3.3.

Recognising the techno-economic paradigm and understanding its implications is **crucially important for the political and policy-shaping of the set of technologies that each revolution provides.**¹⁸ In terms of wealth creation, it is precisely the combination of low-cost factors, new infrastructures and new technologies that allows a leap in productivity and in growth. But each revolution can be led in many directions, suffice it to point out how the fourth – mass production –

¹⁸ There are some similarities here with the innovation journey (Van de Ven et al., 1999) and entrepreneurial ecosystem models (Stam and Van der Ven, 2019), which look at the interplay of factors and actors at the *system* level, and have been applied by Beyond 4.0 consortium members in WP4 and WP8.

revolution was led in radically different ways by Stalin, Hitler and the Keynesian democracies. Even if in the past the understanding had not been explicit, now that we can understand the inter-relations, it is important to take them clearly into account in policy design and in institutional innovation. At a time of networks and platforms, one should not design complex hierarchies; in a rapidly changing context, when jobs for life are rare, unemployment insurance is not the adequate safety net, and so on.

Figure 2. The historical record: Bubble prosperities, recessions and golden ages

No., date, revolution, core country	INSTALLATION PERIOD	TURNING POINT	DEPLOYMENT PERIOD	Maturity/decline
	'Gilded Age' Bubbles	Recessions	'Golden Ages'	
1st 1771 The Industrial Revolution Britain	Canal mania UK	1797–1801	Great British leap	
2nd 1829 Age of Steam and Railways Britain	Railway mania UK	1848–50	The Victorian Boom	
3rd 1875 Age of Steel and heavy Engineering Britain/ USA Germany	London funded global market infrastructure build-up (Argentina, Australia, USA)	1890–95	Belle Époque (Europe)(*) 'Progressive Era' (USA)	
4th 1908 Age of Oil, Autos and Mass Production/USA	The roaring twenties USA Autos, housing, radio, aviation, electricity	Europe 1929–33 USA 1929–43	Post-war Golden age	
5th 1971 The ICT Revolution USA	Internet mania, Telecoms 1990s Global financial casino & housing 2000s	2000-03 2008-20??	Global sustainable 'golden age'?	

We are here

(*) Note an overlap of more than a decade between Deployment 3 and Installation 4

Source: Perez, 2016, p.195

4.3 Recurrence of loss and gain: the socio-economic impact of the patterns of installation and deployment

Each installation period brings with it fears that skills, jobs, industries, and entire regions will be decimated – and these fears are not unfounded. The machines of the first revolution displaced the cotton spinners in England at the same time as the productivity increases in agriculture created such levels of rural unemployment and hunger that parishes felt compelled to provide a type of 'basic income' (the Speenhamland system). The second revolution led to the Chartist movement and major labour unrest, in reaction to the harsh conditions of early industrialisation. The third, in which the US and Germany began to forge ahead of Britain, was the first globalisation, which brought about a very complex process of 'winners' and 'losers', among countries, regions, sectors and workers. The recent fourth surge, with the introduction of the assembly line and the mechanisation of agriculture, led to massive job destruction, especially visible in the 1920s and 30s. It was difficult during the Depression to imagine that the emaciated workers queueing at the soup kitchens could soon own a suburban home with a car at the door.

And yet, in all these cases, what followed in the industrialising nations were better times, with growing employment and measures for social welfare. We shall delve deeper into employment losses and gains for each shift in T7.2 and T7.3 of this project, and in the related deliverable. What is crucial to understand here is that these fears – and the very real destruction and inequality that underpin them – heighten during the latter years of deployment, reaching a zenith during the Turning Point. This is where we are at this moment in time – Spring 2022 – and, from this vantage point, the patterns of loss and gain are not always apparent.

Take the now well-known US inequality data highlighted by Piketty and Saez (2003). This was the result of an extensive project to pull together a long-run inequality series dating back to the start of the 20th century, previously not attempted due to the lack of available comparable statistics. Yet despite such a huge effort on the part of the authors, and those others inspired to produce similar research for other countries, this extremely ‘long-run’ series in economics terms only captures one full revolution, according to the dating set out above. It begins and ends mid-surge, thus obscuring the longer-term patterns of diffusion. Analysing the US within that single century time frame, and with a political concern on the present concentration of wealth, Picketty, in his later work (2013), is one of many scholars to refer to the reduction of inequality post-war as ‘exception’ to the polarising tendencies of industrial capitalism.

However, in the earlier paper with Saez, the two authors refer to the rising of the trend after the 1970s as a possible ‘second Kuznets curve’ (see Section 2.1). This supports the neo-Schumpeterian view, which analyses multiple shifts in job creation, wages, industrial growth and so on, capturing the trends of inequality and welfare beyond a single data set. Using these analytical tools, the ‘exception’ becomes part of a regular pattern.

Each installation period has been a process of income polarisation between winners and losers, resulting from the elimination of skills and industries and devastation of previously profitable regions. In every case, there have been new millionaires, new wealth concentrating in the hands of novel entrepreneurs and bold and ruthless investors and speculators. Then, when the inevitable bubble has collapsed (see Figure 2), governments – typically prompted by the work of social movements – have stepped in to reverse some of the worst social consequences of the ‘creative destruction’ process and to regulate the negative behaviour of the financial world. This reversal has occurred to a different degree with each revolution, and each time only partially driven by humanitarian concerns, or even by fears of (notably socialist) insurrections – although such insurrections have indeed been subdued as a result. What lies behind a great many worker concessions and welfare policies has been the need to support economic growth following times of social and economic turbulence; the benefits of that prosperity have then led to relative peace.

During the Victorian boom, Engels (1857) wrote to Marx warning him not to expect the working classes to rebel because ‘the long period of prosperity is bound to have made the masses damn lethargic’ – and indeed, the workers’ rebellions of the 1840s were fast being replaced by organised trade unions. The deployment period of the next surge brought the Progressive Era in the US, during which various social movements and the government tried to reduce unacceptable poverty and counteract bad living and working conditions, as well as to protect consumers and smaller producers from the excess power of trusts and monopolies. In Britain, Lloyd George set up an early version of the Welfare State in 1906 with the ‘People’s Budget’, explicitly aimed at diminishing the appalling

dereliction that had been described in reports by Booth (1889-1902) and Rowntree (1901). In Germany, where Bismarck had pioneered such measures in the 1880s to counter religious and political instability, the policies were expanded and intensified in the 1900s. Most European countries set up similar social security policies in the Belle Époque. Mortgages, unemployment insurance, loans, free education and healthcare were then instrumental to unleashing the deployment of suburbanisation and mass consumption post-WWII, and decades of prosperity.

Indeed, regardless of the motivation or its enactment, these government interventions have been key to the successful, directional deployment of each revolution, bringing the 'bounty' and 'spread' of the new revolution, to borrow Brynjolfsson and McAfee's terms, from concentration in the hands of the wealthy few to the benefit of an ever-larger demographic. And though only spanning the beginning of the fourth revolution to the early installation of the fifth, that is clearly what the Piketty and Saez data show. Both in the installation period of the mass production revolution – in the 1910s and 1920s – and in that of the current ICT one – from the 1980s to the 2000s – the income share of the top 1% of taxpayers tends to reach 25%. This inequality was reversed by government policy in the post-war period – from high taxation to redistribution, and by regulating business towards providing for a new way of living, as we shall describe in the next section — in what has been the most successful positive-sum game in the history of capitalism (see figure 1).

Thus, the progress from the 'satanic mills' to the workers of the advanced world acquiring 'middle class' status has been a turbulent journey from one technological revolution to another, from skill destruction to job creation and back, with each revolution leading to larger numbers being incorporated into better lives. In the First Industrial Revolution, it was only the merchant and industrial classes that joined the aristocracy; in the second, the skilled and educated layers, especially those who provided trade and services in the growing cities, reached more comfortable living. It was in the third surge, the Age of Steel and Heavy engineering, when, for the first time, a layer of the working class was lifted to better lives. The new high-tech industries, chemical, electrical, civil, naval required high skills and paid for them; at the time, the expression 'worker aristocracy' was used to refer to their privileged status. It is with mass production in the fourth surge that mass consumption reaches the majority of blue-collar workers. The geographical spread of socio-economic advance was also increased – from the core industrial countries of Europe in the 19th century, to the Americas (in varying degrees) and Australasia in the third revolution, to the BRIC nations in the fifth.

However – and this is a big however – not everybody has benefitted, some have benefitted more than others, and some revolutions have seen less spread. While the mass consumption revolution led to the 'trente glorieuses' in the West, the countries of what was then called 'the third world' were exploited and excluded, relegated to raw materials production confronting the price scissors identified by Singer (1950) and Prebisch (1950). Even within those countries that saw general prosperity rise, regions, jobs and lives were destroyed, sectors of society excluded and the environment seriously endangered. The promising technologies of each revolution, and ways in which they have been deployed, have created each time a new raft of problems to deal with in the next.

We now have the benefit of hindsight. We need to move beyond a binary vision that sees the socio-economic impact of technological change either as leading to the loss of skills, jobs and industries,

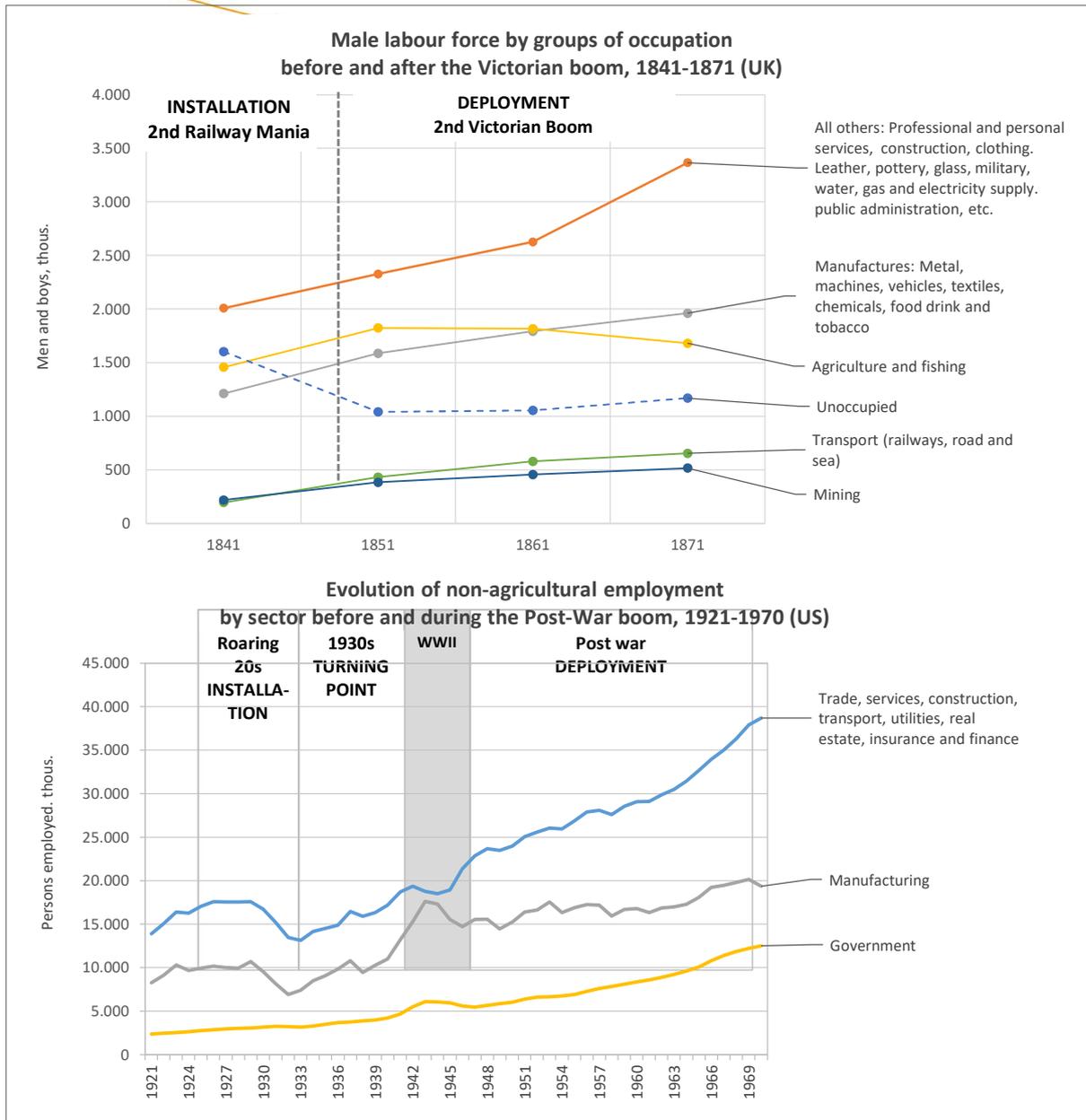
or as the inexorable march of progress, which, while causing destruction and suffering en route, sees a growing number of the world's population lifted out of poverty. Both tell part-truths – but only by understanding the role of social and political forces in shaping the context and the direction of technology will we be able to play an active role in achieving the best social outcome from the potential of each specific revolution. We shall return to this in Section Four.

4.4 The role of paradigm shifts in lifestyles in the transformation of jobs and employment

While every technological revolution inevitably destroys many jobs and skills, historically, unemployment does not remain high or even increase in the long term: each revolution also creates jobs and skills that were previously unimagined. But **the victims are not necessarily the beneficiaries of the new opportunities – and the jobs created are not where many of the techno-optimists predict, nor where the unemployed are located, nor suitable to their existing skills.** Even if the statistics give a good picture, 'creative destruction' is deeply painful for its many victims. What is often missed in the analyses of revolutions is that **the majority of new jobs will not be in the new 'high tech sectors' of each revolution, but rather that the revolution and the techno-economic paradigm it gives rise to lead to new lifestyles that create a range of new forms of demand for multiple goods and services which were not available previously.** Victorian living was different in its requirements from the countryside aristocratic way of life; in turn, the cosmopolitan living of the Belle Epoque created new demands, as did the suburban 'American Way of Life' after World War Two. This can be clearly seen in Figure 3, which shows the distribution of employment in the second and fourth golden ages.

The neo-Schumpeterian interpretation thus includes both the destruction and creation of jobs and skills not as an automatic process but as part of a socio-political transformation in which the State plays a key role. Without changes in the context and in the relative cost structure to guide innovation and investment in clear synergistic directions, destroyed jobs are not replaced, and the deployment period does not result in a golden age.

Figure 3. Distribution of employment by sectors in the Victorian boom and the Post War Golden Age



Sources: 3.1: Mitchell (1988) Table II-2. Based on 1911 census categories (our period indications); 3.2: US Dept. of Commerce. Historical Statistics (our period indications).

5. Adapting to the technologically inevitable or shaping the options through policy?

The various approaches to the study of long economic cycles and/or technological revolutions have usually focused on explaining and describing what happened in the past, what is happening in the present and/or what is likely to happen in the future. **Few are geared towards learning the way in which society, through politics and policy, oriented each technological revolution towards better or worse outcomes.**

Although there are exceptions, as always, those working in the long-wave tradition, with its emphasis on statistics, have tended to be in the job of explaining cyclicalities, not of taming it. Economic historians describe, analyse, explain and, at times, use historical parallels to predict outcomes, but do not, typically, identify how to modify such outcomes in a socially beneficial direction. The neo-Marxists have, generally, wanted to effect change in the present, but their focus is on criticising the nature of the system and of replacing it with another, not on identifying the existing mechanisms that could be modified through transition. The meso-level theorists concentrate on the power of innovation, at times forgetting that social processes also need to change.

However, as already noted, both scholarly and popular interest in ‘long waves’ has been as cyclical as the revolutions themselves. It may be that the statistical view of upswings and downswings is more popular in deep recessions and that the attribution to new technology gains ground when technical change is most visible, its future most threatening and its effects less predictable. Certainly, that is a shift one could infer from our findings (see Appendix). At that point, there is likely to be a division between those who see the future as adapting to the inevitable and those who consider it possible to shape the options. That is where we have been since the financial crisis of 2008, in a debate that has become even more pertinent as we face the aftermath of the COVID-19 pandemic.

5.1 Techno-optimist, techno-pessimist – or techno-determinist?

Over the past decade or so, increasing attention has been paid to the transformative power of the new digital technologies, particularly artificial intelligence (AI), robotics and the Internet of Things (IoT). They are either celebrated or feared, giving way to a debate between techno-optimists and techno-pessimists. **However, when closely analysed, both perspectives can be viewed as technologically deterministic, even when the proponents may not see themselves as such** (Table 2). Whether technologies are perceived as good or bad for society, the results of their diffusion are seen as intrinsic to their nature, and the consequences as inevitable. **The most we can do, goes this line of thought, is adapt to the inexorable path of technological change while mitigating its worst effects.**

Table 3. Categorisation of perspectives on technological revolutions

	Pessimistic	Optimistic
Non-determinists	Neo-Marxists	Schwab Freeman/Louçã/Perez Geels/Schot Tylecote
Determinists	Robert Gordon Frey & Osborne	Brynjolfsson & McAfee

As already noted, typical of the techno-optimists are MIT’s Brynjolfsson and McAfee, who see the advanced digital – ‘brilliant’ – technologies replacing mental labour or, at best, leading to collaboration between humans and intelligent machines (Brynjolfsson and McAfee, 2014). The power of artificial intelligence, robotics and others is celebrated for its potential to increase productivity even as humans work less. While they recognise that the unemployment and inequality that follows are serious threats, they provide no suggestions to significantly avoid or mitigate them, beyond tinkering at the margins. Perez (2018) analyses the limitations of the Brynjolfsson and McAfee analysis, notably the division of history into only two periods. We shall not repeat the entire argument here, not only due to space but also because most of the authors covered see at least four revolutions, if not five or even six (Mathews, 2013; Wilenius, 2017). However, there are key elements of critique that also apply to other scholars of historical technological change. Although Brynjolfsson and McAfee assert that we face a momentous transformation, **the policies that they propose are rooted in the economic orthodoxy of the past few decades, which neither understands technical change nor takes it into account.** In fact, their recommendations are extremely timid when compared with the widespread economic and policy changes that were needed to address previous transformations. **Unfortunately, their choice of periodisation blinds them to the upswings and downswings in the role of government which have accompanied every surge of development.**

The neo-Schumpeterian perspective recognises, however, that it is in the nature of the early, creative destruction period that government takes a more hands-off approach, whilst in the turning point that follows a crash, one sees radical institutional and policy transformations – such as the ‘municipal’ forms of a nascent welfare state during the European Belle Epoque and the Progressive Era of the US (Fraser 1984) and the massive intervention of government in the economy that brought prosperity following World War II. **Thus arguments for a more regulatory State and those in favour of a laissez-faire approach can be seen to have been appropriate – but at the relevant times of each surge,** and with the recognition that any form of hands-off in terms of regulation is still an active policy choice.

Furthermore, while Brynjolfsson and McAfee’s thorough understanding of the ICT revolution allows them to see its consequences for the outdated production methods and lifestyles associated with the mass production revolution, their lack of attention as to how previous technological transformations have disseminated across society limits their vision of the possible role of ICT in enabling truly new directions for both economic growth and institutional and social change on a

global scale. Similarly, concentrating only on high tech changes blinds them to the job creation potential of a green transition and the related new lifestyles that could emerge.¹⁹

The work of Frey and Osborne can also be seen to exhibit **this focus on the destruction of the present rather than the reimagination of the future**. Not only does their joint research predict the decimation of present jobs without consideration of those that might not yet exist (Frey and Osborne, 2013), but Frey's only hope for those whose jobs are threatened is limited to factors that can reduce the speed of diffusion (which includes government regulation aiming at such a slowing down) (Frey, 2019).

The centring of the United States by Brynjolfsson and McAfee is also evident in the arguments of R. Gordon, who confronts them from the techno-pessimist camp. Gordon too remains locked into a world that regards the US as the central player on the global stage – a role that it did not hold for the first 150 years of industrialisation, and which a closer analysis of history would make clear is by no means a given for the future. **This prevents both optimists and pessimists from reimagining comparative advantage for a world in which technology is increasingly connecting every locality to the global economy**; where decentralised networks and niche production can coexist with economies of scale, scope and networks; and where a multi-polar world might eventually replace the single-hegemon model experienced up to now.

In addition, Gordon focuses on technologies past and present, failing to recognise human agency in the process of shaping their dissemination. Being profoundly sceptical of the power of the current information revolution, which he sees as having a minor impact on growth, productivity and well-being, he is concerned about the probable decline in living standards. Hence, he proposes several policy measures to safeguard society and improve conditions, but does not consider any government action to influence technology directly.

5.2 State and society set the direction for technology

Thus, **the majority of the current approaches to understanding the present moment as a technological revolution fail to understand how government and society, for better or worse, can re-direct the potential of each technological transition**. Often inadvertently deterministic, they do not envisage shaping the course of technology now, as was clear, for example, in the post-war boom by Hitler, Stalin and the Keynesian democracies, with very differing goals and results. Even within the capitalist democracies there was and is significant variety. As Hall and Soskice (2001) suggest, the range goes from the 'liberal economies' such as the US, Australia and the UK, through the 'coordinated economies' of Germany, Japan or Italy, to the Nordic Model across Scandinavia.²⁰ **Such differing socio-political frameworks resulted in significant diversity in the way that business and society have been organised**. These were all market economies, using and shaping the power of the same mass-production revolution, but each with a socio-political framework that developed in a specific historical context, reflecting different cultural and political values. And they have all since

¹⁹ We shall explain this point in detail in the next deliverable. See further 'Second Machine Age or Fifth Technological Revolution?' <http://beyondthetechrevolution.com/blog/second-machine-age-or-fifth-technological-revolution/>

²⁰ And within these groupings, there are also significant differences. For example, the 'coordinated economy' of the Netherlands may be strongly coordinated regarding the social welfare and distribution agenda, but not in terms of innovation and R&D programmes; Germany places an emphasis on both. Thank you to Peter Oeij for this observation.

begun to respond differently to the disruptions and opportunities brought by the ICT revolution and the globalisation it enabled.²¹

The neo-Schumpeterian contention is that each of the five surges of development to date, being the process of assimilation and deployment of each technological revolution, has both common and unique features in relation to the others. The uniqueness comes mainly from the nature of the technologies and of the specific historical context; the commonality from the more predictable nature of human behaviour and of social change processes in the context of capitalism. **Research following the five surges model suggests that the recurring sequence is caused by this commonality, not by anything intrinsic to the technologies.**

The development of each techno-economic paradigm very much depends on the capacity of society and governments to realise the huge transformative potential that each particular technological revolution installs, and to generate a context and a specific type of dynamic demand that can bring forth the innovations and investment that are there to be unleashed. Like the development of individual innovative products and processes, a viable direction for growth in each new technological paradigm first presents itself in niche endeavours, as the work of the meso-level transitions theorists have made clear (Geels, 2002). But during the turning point of each surge the playing field must be tilted in a general direction that will make innovation less risky in terms of demand, and investment more profitable (Perez, 2016).

Thus the social shaping option recognises the whole range of what technology can do and, without opposing its new power, selects a directional path from within the range of the viable. Schwab's 4.0 proposition, while it does not provide the wealth of historical detail nor depth of understanding of many of the perspectives that we have discussed here, does not fall prey to determinism, recognising the need for directionality (Mazzucato and Perez, 2015). **However, many of those who take up the Industrie/y 4.0 clarion call blindly, without questioning the framework, unfortunately, fall into techno-determinism (whether optimistic or pessimistic).** Given the need to fully grasp the transformative potential of the non-deterministic approaches, therefore, it is to the nuances in the differences between Schwab's approach and that of the neo-Schumpeterians that we shall focus on to conclude.

²¹ Given that the focus of this paper is on the study, framing and implications of that framing, of technological revolutions in the West, it is beyond our scope here to look here at the experience of contemporary China, or indeed any of the Asian tigers. It is however clear that, in all those cases, dynamic markets have been supported and helped by strongly proactive governments promoting the acquisition of the latest technologies, educating the population and shaping the direction of investment and innovation. Analyses of Japan (Johnson, 1982) Korea (Amsden, 1990) Taiwan (Wade, 1990) and China (Naughton, 2021) give ample evidence of this.

6. Industry 4.0 and the five surges model: complementary theories for informed policy

In terms of policy, it should be clear that a discussion rooted in the perspective that technologies can be shaped in order to achieve socio-economic goals such as more employment opportunities, greater work satisfaction, better living conditions and greater social equality will be more productive. Market-shaping industrial and innovation policy is social policy (Mazzucato et al., 2020). In the present transition, recognising that it is possible to shape it in a direction that addresses the need to confront the challenge of environmental sustainability is also crucial. It is important for those working with this goal to understand the **similarities and differences** between Schwab's Industry 4.0 approach and that of Perez and the neo-Schumpeterians – and the benefits of combining the two.

6.1 Areas of coincidence

Both approaches recognise technological revolutions as the form taken by major advances in capitalism. While it is common today for economists and policymakers to follow Schumpeter in seeing innovation as key to economic growth, taking these perspectives allows us to understand the role of such waves of technical change as the source of progress and improvements in terms of productivity, while also as the periodic driver of destruction and/or changes in the nature of many jobs and skills. Yet rather than shrink in fear at these changes, or blithely assume that the technologies themselves will provide solutions to the destruction they create, neither slips into technological determinism. Both have the foresight – with the benefit of historical example and the lessons of the innovation scholars – to read activity at the niche level and see and/or imagine the existence of a wide range of different possibilities for the deployment of each revolution and of each of its component technologies. This foresight is accompanied by the consideration that it is crucial to understand the nature and potential of the new technologies in order to be able to shape them. **Though both approaches are techno-optimistic in the sense that the greater productivity attainable can improve society, they both also hold that technologies are only tools to be guided. Technologies and the temporal and geographical context sets the stage; society decides how to use them.**

6.2 Key differences

Definition of technological revolutions: While **Schwab concentrates on the main technologies** that influence the changes in industry, **Perez sees a combination of specific and recurring elements** (infrastructures, inputs, machinery, consumer products, organisational models, etc.) all changing the 'common sense best practice' – **the techno-economic paradigm**, or what others in the Beyond 4.0 project recognise as the technosocioeconomic-ecosystem – for investment and innovation, for the 'what and how' of production and also of consumption. **It is primarily this difference that leads**

Schwab to see the present moment as the beginning of the fourth revolution, while Perez' understanding of previous socio-economic surges of development reads it as the mid-point of the fifth.

Recurrence: Perez identifies the cause of each revolution as the maturation and then exhaustion of the previous one, and **understands the sequence of interactions between finance, production and the state as constituting a regular sequence of propagation**. Schwab does not identify any specific similarities in the successive diffusion processes, beyond there being a major transformation in all aspects of production and life; neither does he identify the cause of such upheavals or any recurrent sequences in their diffusion.

Focus of attention: Schwab concentrates on the nature of the newest technologies, their potential and their positive and negative consequences in order to move society to favour the positive and avoid the negative. Perez studies the entire economy in order to grasp the potential for shaping not only the frontier technologies singled out by Schwab, but also the many less advanced but equally new technologies – such as, in the present moment, solar panels and regenerative agriculture – as well as **the employment-creating technologies that may be of much lower productivity and not initially present as high-tech, yet are shaped by the new paradigm** – maintenance services in a rental model replacing a consumption one, for example.

Focus of research: As a consequence of the differences in focus, those following the Industry 4.0 approach tend to concentrate on identifying the various uses of AI, robotics, IoT and CRISPR; how business puts them to use; their consequences; and the speed of their diffusion. Perez undertakes long term historical research in order to understand the complex process of adoption, shaping and diffusion of previous revolutions. Only then is this complemented with the analysis of current challenges and potential policy directions. She aims **to understand how governments at various levels are trying (or not trying) to shape technologies towards paths that will reduce inequality, increase employment and wages, educate, skill/reskill the workforce and tackle the pressures on the environment**. She looks at the **modernisation of government in their organisations and methods** – Mazzucato's missions (Mazzucato, 2021), Kate Raworth's Doughnut economics (Raworth, 2017), O'Reilly's platforms (O'Reilly, 2011) – and the **possibilities of devolution**, down to cities and municipalities and up to supranational bodies. None of these aspects can be properly analysed nor recommendations provided without an understanding of both the historical patterns and the nature of the current technologies and their paradigm, in contrast with the previous ones.

Agents of change: Schwab sees all stakeholders as equally important in the process – business, workers, consumers and government – while – perhaps not surprisingly given his WEF position – seeming to focus particularly on the role of responsible business. **For Perez, while all stakeholders play a role, her analysis suggests that their relative importance changes with the different periods of diffusion in each revolution**. In particular, she holds that government policy is predominant once finance has played its role and the technologies are installed, with their potential for good and ill ready to be recognised and shaped.

Theoretical context: The Freeman-Perez theory is embedded in a school of thought, Evolutionary Economics, and within the wider field of Science and Technology Studies, enriched by the Transitions School. Schwab's work draws on his wealth of experience in industry and as an academic engineer and economist, and is rooted in WEF discussions and projects (Schwab, 2016, p.10). **While**

he himself has a long background in academic economics, the 4.0 theory is not enveloped in any of the various social science research threads in relation to technical change. Nevertheless, his views are now predominant in new papers and popular discussion on the topic.

6.3 Why and how are the approaches complementary?

The spread of technological revolutions and their effect on employment involve complex compensating mechanisms when seen at the macro level. The mechanisation of agriculture was compensated by the booming of manufacturing in the cities; the deskilling of industrial workers by the assembly line was compensated by the growth of construction and multiple services for suburban living; the effects of AI and robotics could well be counteracted by the green transformation. It is towards this wider assessment of the future and of the ways to shape it that the neo-Schumpeterian approach is a useful contributor.

Nevertheless, it is undeniable that the most threatening new technologies when it comes to employment are the ones on which Schwab focuses. Painstakingly documenting technology after technology and application after application, his detailed analysis of AI, robotics, IoT, and, to a lesser extent, the newest biotechnologies, can go a long way to informing us on how to avoid the worst consequences while benefitting from their positive possibilities.

Yet another encouraging aspect of the Schwab and WEF approach is the effort to identify all the possible stakeholders – business, workers, consumers, government – as actors in the shaping process. Most importantly, the effort to bring them all together in the Davos meetings and to keep a large organisation doing research for the World Economic Forum, is a most valuable contribution to the understanding of the need to shape the new technologies and the possibility of doing so.

Within this social shaping goal, the importance of the meso-level transition school discussed above must not be ignored. Their theories can help us to understand the processes of transition in an interdisciplinary way, including all the factors and agents that intervene. Many of the discoveries as to how companies, whole industries or whole sectors evolve from one socio-technical regime to another are directly applicable to what is discussed by both schools being compared here.

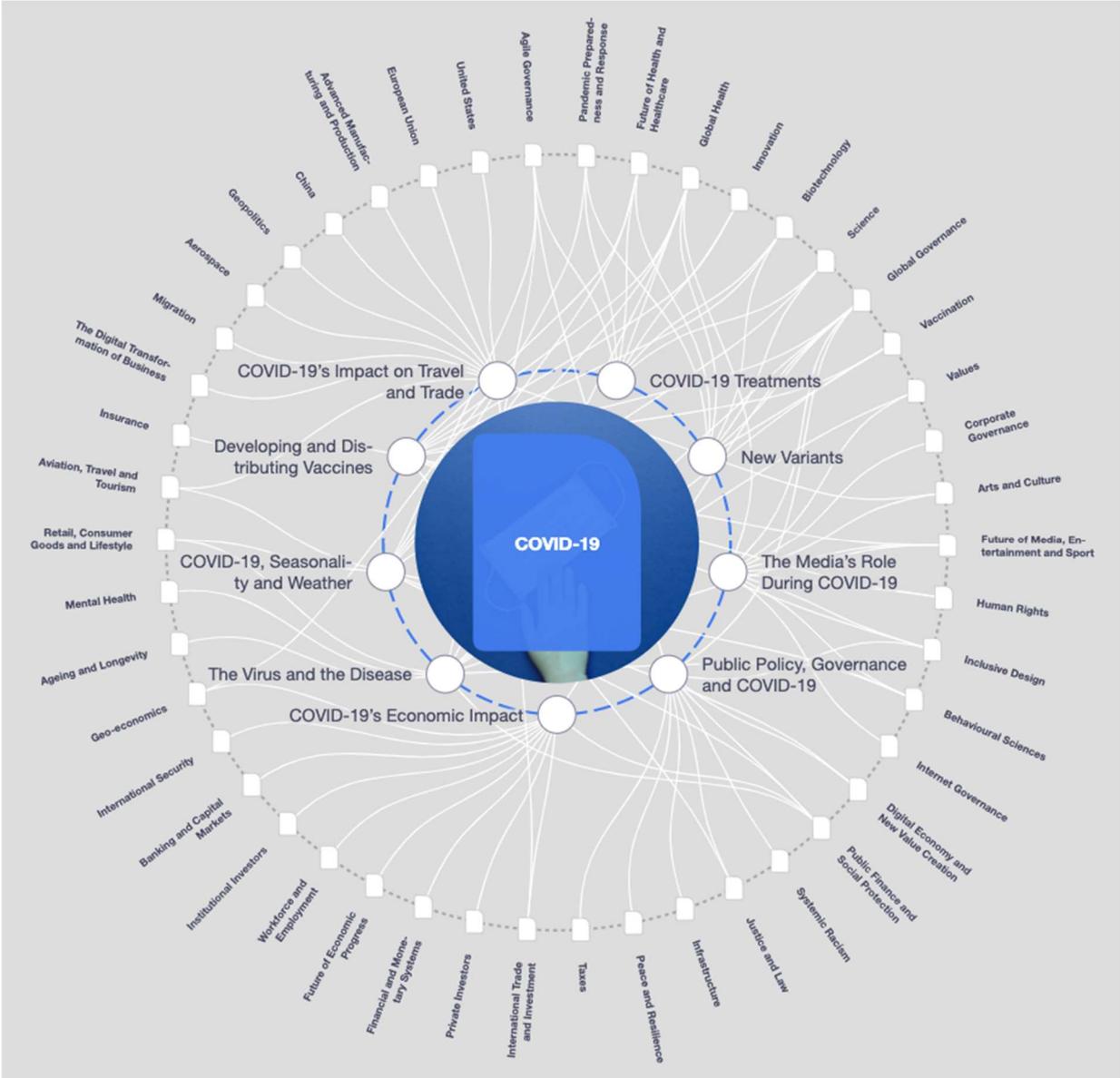
6.4 A leap ahead with broader and more ambitious policy goals

Two years after his first book on the 'Fourth Industrial Revolution', Schwab provides an extended version, the title of which indicates the difference between the two books. *Shaping the Future of the Fourth Industrial Revolution: A Guide to Building A Better World* (2018, written with Nicholas Davis) makes a leap toward the clearly-stated goal. Yet the same shortcomings already discussed are present. Among them is the concentration on the frontier technologies only; however, history shows that the system requires a multiplicity of technologies and the absence of the impending environmental threats. Moreover, rather than use those technologies to solve the challenges faced by society, the focus is on the technologies and how to shape them to improve the world, at the risk of missing important problems, as well as non-technological solutions.

A greater leap is made in Schwab and Malleret (2020), which widens considerably the scope of the changes required, and adopts a more comprehensive approach to the necessary transformation in

light of the COVID-19 pandemic, one that includes the need to tackle inequality, global health and environmental sustainability, with greater state intervention to guide technology and the role that it plays in the economy. Figure 4 presents a graphic summary from the World Economic Forum.

Figure 4. COVID-19: The Great RESET



Source: This online interactive 'Transformation Map' of the issues around COVID-19 has been developed by the World Economic Forum as part of its Strategic Intelligence initiative. Curated by Georgetown University, the nine central topics are available to view without membership subscription at: <https://intelligence.weforum.org/topics/a1G0X000006O6EHUA0?tab=publications>

However, Schwab and Malleret attribute the pressing necessity for this 'reset' as a response to the pandemic, which they see as a fundamental inflexion point in our global trajectory, rather than noting – as Freeman and Perez would – that **all the problems starkly exposed by COVID-19 already existed prior to the pandemic, and result from the manner in which finance, business and governments have faced the information and communications (ICT) revolution since the 1970s and**

80s. Without this understanding, there is a risk that, rather than 'reset', policymakers will drift towards the tendency to legislate for 'business as usual'; what is, in fact, an impossible return to the gilded prosperity of the creative destruction era. Even with the great innovation and entrepreneurial successes of past decades, this unwillingness for radical change along the lines of the great transformation that followed WWII has been in effect since the crash of 2008, and prevented such a transition from occurring.

7. Some concluding words

The current popularity of the notion that we are in the midst of a ‘Fourth Industrial Revolution’ comes at a time when the growing inequality characterising the past few decades has become evermore unacceptable and its reversal evermore urgent. **The COVID-19 pandemic has not only increased that sense of urgency, but also brought into focus the role of innovation in solving major problems such as global health – and the power of governments to both foster that innovation and support the economy in multiple ways.**

In these circumstances, **the role of technology, as a set of tools** that can both solve existing problems – such as unemployment, environmental damage and global inequality – and create similar problems of its own is being increasingly recognised. In particular, the answers to the questions of its degree of inevitability, of its possible or negative effects and of society’s capacity or incapacity to shape it for the common good, are becoming essential. **All too often, the pronouncements that we are in a technological revolution come both without critical interrogation, and with an underlying bias toward technological determinism.**

In this paper, we have tried to map the various avenues pursued by scholars of technological evolution, from the ones who see it dimly as the possible cause of major economic fluctuations, through those who focus on one or another of the particular changes it produces – be it in politics, society, work, production practices or employment – to those who emphasise the mutual influence between technology and society. We have tried to illustrate how the different framings can lead to different understandings of how best to act now. It is our contention that **the neo-Schumpeterian identification of the recurring historical pattern in the propagation of technological revolutions and the role played in each period by finance, production, politics and government policy is particularly useful for identifying the opportunities for social shaping.** At the same time, the understanding of the processes provided by the Dutch transitions school can illuminate the types of action and the roles played by the different actors in each of the sectors. In addition, a useful method for guiding the actual process of change is the work of Mariana Mazzucato on the use of ‘missions’, a practice that can be adopted by governments to bring together the action of multiple agents in society all focused on achieving one after another of the desired goals (Mazzucato, 2021).

Armed with this deeper understanding, the route to a better future can be helped by the many scholars who are taking up the Industry 4.0 framing to analyse the specific risks and promises of the frontier technologies in each of the areas where they influence change. A technological revolution is a massive process of change across society, affecting and affected by everything from geopolitics to lifestyles. Understanding the way such changes have been faced historically is likely to increase the chances of success in overcoming the major threats confronting humanity today, and in building a socially and environmentally sustainable world.

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APPENDIX: Findings and reflections of database searches on 'technological/industrial revolutions'

A.1 Introduction

The Appendix discusses the early-stage work of Task 7.1: manual and systematic searches of databases and academic journals of the key intellectual threads in the study of the dynamics of technological revolutions, as well as various access points to the popular discourse on the topic.

This is not a dumping ground for our data; rather, **we cover here what database searches of concepts can tell us – and what they cannot.** As noted in the Approach section of the paper, we are cautious of the limitations of such searches – more broadly, as a tool of the social sciences, particularly when one moves away from searching purely empirical studies; and specifically, in the case of this topic. **This is an extension of a primary theme of the paper: that the framing of data can obscure as much as it reveals, and that the framing of data is as key to our understanding as the data itself.**

In what follows, we first interrogate the terms and definitions used in the discussion of technological/industrial revolutions, and follow this with an analysis of the use of these terms over time, looking at Google NGram and Scientific American. We then detail and reflect on the results of our surveys of Google Books and Google Scholar; the Web of Science, Scopus and other academic databases; and those journals which proved to be most fruitful for our search.

A.2 Terms and definitions

Our first task in attempting a search of the literature was to wrestle with the problem of poorly defined terms. **‘Technological revolution/s’ has become a slippery concept, used across different academic disciplines and, increasingly, in popular discourse.** And whilst it is the preferred term of the paper’s primary author to describe her periodisations of technological change, **‘industrial revolutions’** has always been an alternative term, and is currently more common in usage, popularised by the work of Schwab (see Introduction). **It is equally as poorly defined.** Other authors discussed in the paper eschew ‘revolutions’ altogether, or use it alongside ‘long waves’, ‘economic cycles’, or, like the author, ‘surges of development’, often blending the two, so that, for example, the author of this paper will be included in a survey on ‘long wave’ authors yet themselves does not hold that their work is on long waves (see Section 3.1 of the main paper).

In the main paper, we discuss the many disagreements as to what these ‘technological revolutions’ or ‘industrial revolutions’ refer: on the number of revolutions; on when one has ended and another begun; on what have been the drivers and the immediate and long-term consequences. To some scholars, ‘revolutions’ describes big bang moments, either particular inventions, and/or short periods in time in which a number of inventions cluster and technology, and therefore society, undergoes a fundamental shift. Note that the word ‘invention’ is used here deliberately, rather than innovation; at the most simplistic, a ‘technological revolution’ may be used to indicate not much more than, for example, the steam engine and spinning jenny.

More multi-faceted analyses use ‘technological revolutions’ to describe not a change in a limited number of technologies nor a change in energy source, but as interconnected clusters of new and dynamic inputs, processes, products and industries, and/or of organisational and institutional innovation; a decades-long process of slowly-diffusing change across society. **The interchangeability of ‘industrial’ and ‘technological’ reveals another muddling: when used in its business-derived sense, ‘Industry 4.0’ is often limited to industrial buzzwords such as ‘Smart Manufacturing, Smart Production, or the Internet of Things’** (Kamble et al., 2018). For some writers, technology – especially, but not only in the popular discourse – refers to technological ‘gadgets’ only. Yet the neo-Schumpeterians see ‘technology’ as something far broader:

The tools, the knowledge and the experience used in the design, production and distribution of goods and services, including both organisational and technical aspects. (Perez, 2002, chapter 2)

while technological revolutions are:

... a powerful and highly visible cluster of new and dynamic technologies, products and industries, capable of bringing about an upheaval in the whole fabric of the economy and of propelling a long-term upsurge of development. It is a strongly interrelated constellation of technical innovations, generally including an important all-pervasive low-cost input, often a source of energy, sometimes a crucial material, plus significant new products and processes and a new infrastructure. The latter usually changes the frontier in speed and reliability of transportation and communications, while drastically reducing their cost. (ibid)

Which in turn are inextricably linked to ‘great surges of development’:

... 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 process evolves from small beginnings, in restricted sectors and geographic regions, and ends up encompassing the bulk of activities in the core country or countries and diffusing out towards further and further peripheries, depending on the capacity of the transport and communications infrastructures. (ibid)

Producing a new 'techno-economic paradigm' (TEP):

A techno-economic paradigm is a best-practice model made up of a set of all-pervasive generic technological and organizational principles, which represent the most effective way of applying a particular technological revolution and of using it for modernizing and rejuvenating the whole of the economy. When generally adopted, these principles become the common-sense basis for organising any activity and for structuring any institution. (ibid)

Such an all-encompassing socio-economic paradigm shift is reflected in the way that Industry 4.0 has been used and popularised by Schwab. They are also the definitions from which we work within the main paper, as it is written from a critical neo-Schumpeterian perspective, and the principal investigator's own. However, as our searches below illustrate, 'technological' or 'industrial revolution' are alternately used to describe such paradigmatic shifts and employed for the more specific industrial changes – and **the meaning is typically assumed rather than defined, let alone queried.**

Companion terms used in searches

Given that, as discussed above, Perez is one of only a few authors to use 'technological revolutions' as a key phrase and in the title of her work, and that 'industrial revolution/s' is often used to refer to a specific historical period, we used other keywords in conjunction with those two phrases when performing the database searches. These included: innovation, technical/technological change, industrial policy, economic growth, economic development, economic history; definition of, theory of, history of, measurement of, and literature / systematic review of. We also considered works and journals from multiple fields, including: innovation studies, technology/ technological studies, philosophy of technology, economic history, economic development, economics, business economics, heterodox economics, political economy, sociology, and management studies.

A.3 Google NGRAM

With the Google Books Ngram Viewer (Google Ngram), it is possible to track the popularity of words and phrases over time from the Google Books corpora (Michel et al., 2010). Launched in 2004, the corpora were most recently updated in 2019; over 40 million publications have now been added to the database. **As other scholars have noted, the process is not without inaccuracies and limitations**, from the practical – such as the errors produced by OCR scanning technology – to the population of the corpora, skewed heavily by the volume of academic/scientific literature (Younes and Reips, 2019).

We used the latest edition of the English corpus (English 2019, eng_2019, googlebooks-eng-20200217; US and British English combined), and encountered a number of additional problems in our own searches, particularly when we started to delve into the top ten publications for specific periods of time. These periodisations are automatically assigned each time a search is performed in the Ngram Viewer, and we found that they changed when the same search was replicated on a different day. We resolved this by setting the periodisation manually via the Google Books search; the corpora were the same, but the results produced slightly different results. We discuss this below.

Other issues were less easily rectified. Works originally published by, for example, Kluwer but later published on the Springer digital platform appeared twice; publications were misdated; and some publications ranked high in the search merely because the author cited another author frequently throughout their text; this was the case a few times when Perez's book on technological revolutions was cited.

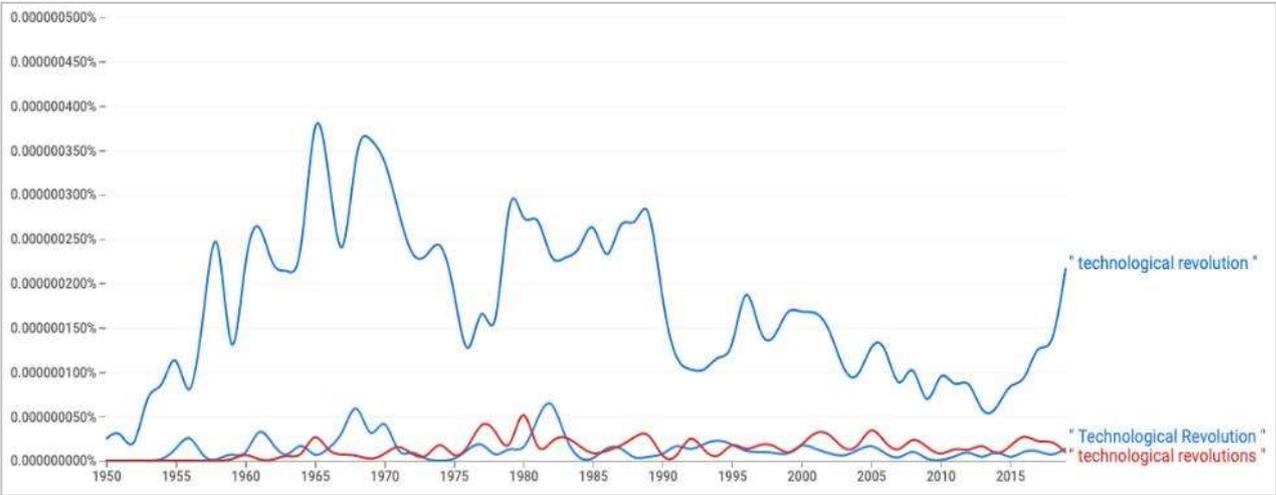
All that said, searching 'technological revolution/s', 'industrial revolution/s' and 'Industry.4.0' (case non-sensitive) **provides a casual snapshot of the popularity of these terms over time**. However, when one more closely examines the individual publications included in the results, as listed in the Google Books section (Section A.4) below, **such a search also reveals the changing nature of the use of terms and the limitations of systematic searching on a terms basis**, in addition to where the usage relates – and does not – to the type of studies that are reviewed in this paper. Note that we expected 'technological revolutions' in the plural to correlate more closely with titles relevant to our topic, while expecting 'industrial revolution' in the singular to be refer more often to the Industrial Revolution of the late 1770s.

Looking first and in the most detail, then, at 'technological revolution' / 'technological revolutions' Ngram (Figure A.3.1), we can immediately see the limitations of what such a search can tell us. Note that Figure 1 starts in 1950, the year that there are records of sufficient use of the phrase (more than 40 per year) to show up on the Ngram (see Figure A.3.2 for details). The phrase 'technological revolutions' is found far less often than the singular – from which one could infer that the discussion of repeating patterns, as in the work studied in this paper, will likely be only a very small fraction of the work that results in any database if the search term 'technological revolution' is employed. And yet, when we examine the individual work in the corpus, that singular search does still bring up the work of Perez and others. In situations such as this, **we would argue one needs the experience of the field in order to employ search terms usefully**; a student/early-stage researcher attempting to grapple with the history of the literature that has attempted to periodise and analyse technological change with the hope of better understanding the present, with little or no prior knowledge of its

lineage, would not get very far by merely inputting the phrase ‘technological revolutions’ into one of the databases.

For the singular, the highest use volume is from the mid-1960s to the early 1970s. When we examine the highest-ranking publications in this period, we see that they are primarily comprised of military and government publications, particularly in policy recommendations regarding the perceived technological flourishing at the time (see section A.4 below). Next is more of a sustained plateau of use than a peak, from around 1980-1990. By this point, the majority of top-ranking works are academic, with a focus on the history of technology and the relationship of technological change to economic change. A smaller burst of activity occurs from 1995-the early 2000s, in which we find the work of Perez (which takes the top three slots for that period, due to the nature of the Ngram system; both the book and two chapters are counted), the start of a focus on ICT and ‘innovation’ as an accompanying, and more publications dealing with technology in the field of international development. After a lull, usage started to climb steeply in 2014. Note that we turned ‘smoothing’ off in our searches, thus the diagrams reflect use per year (Ngrams only register when more than 40 uses of the phrase per year are found). We would recommend looking at these diagrams in the Ngram viewer rather than in the static screenshots we have used here, as this permits zooming in on dates and occurrences. Note that we have not given specific URLs for these images, as they are search date dependent. Source for all Ngram figures: Michel et al., 2010, op.cit.

Figure A.3.1. Use of the phrases ‘technological revolution’ and ‘technological revolutions’ over time, 1950-2019



Comparing ‘industrial revolution’ and ‘industrial revolutions’, (non-case sensitive, no smoothing, as above) is, as expected, somewhat different, although there are similarities. The same point applies to the use of the plural; indeed, although ‘industrial revolution’ has a much higher usage than ‘technological revolution’, the figures for use in the plurals are comparable, supporting both the inference that periodisation literature is only a fraction of the work that will show up using those search terms – but also our belief when deciding on terms that ‘industrial revolution’ rather than ‘technological revolution’ is regularly employed to discuss both a specific period of time in British history and industrialisation in general. The phrase appears much earlier than ‘technological

revolutions’, growing steadily in use from around the 1880s to a huge peak in the 1950s, then dropping off post-1960s fairly steadily until usage started to creep again in 2014. (see Figures A.3.2 and A.3.3). Again, the mid-20th century peak is related to the perceived technological flourishing of the time, and many of the publications are government-related, although this phrase wider academic usage at this stage than ‘technological revolutions’, referring to the Industrial Revolution, as predicted, and Western-style industrial development in general.

Figure A.3.2. Use of the phrases ‘technological revolution/s’ and ‘industrial revolution/s’ over time, 1850-2019

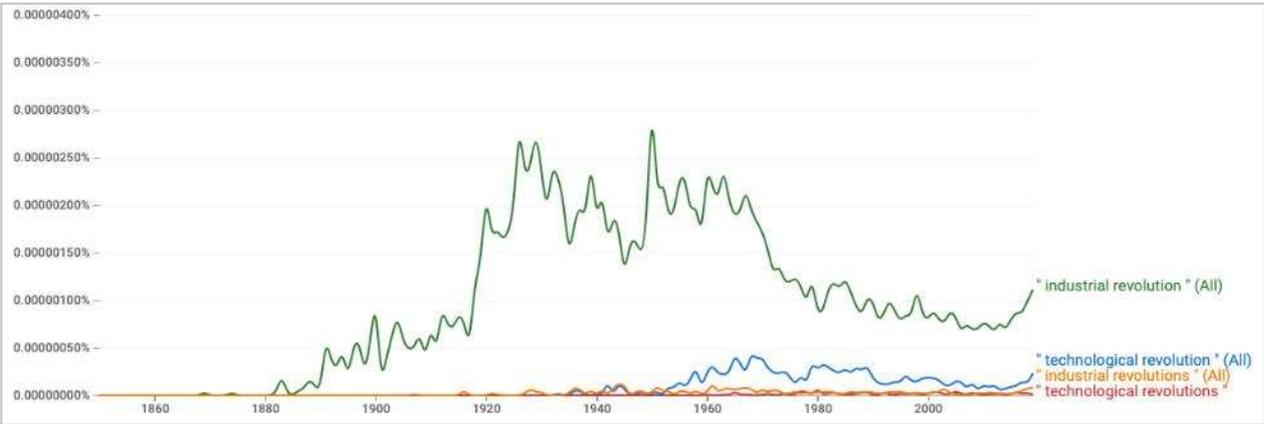
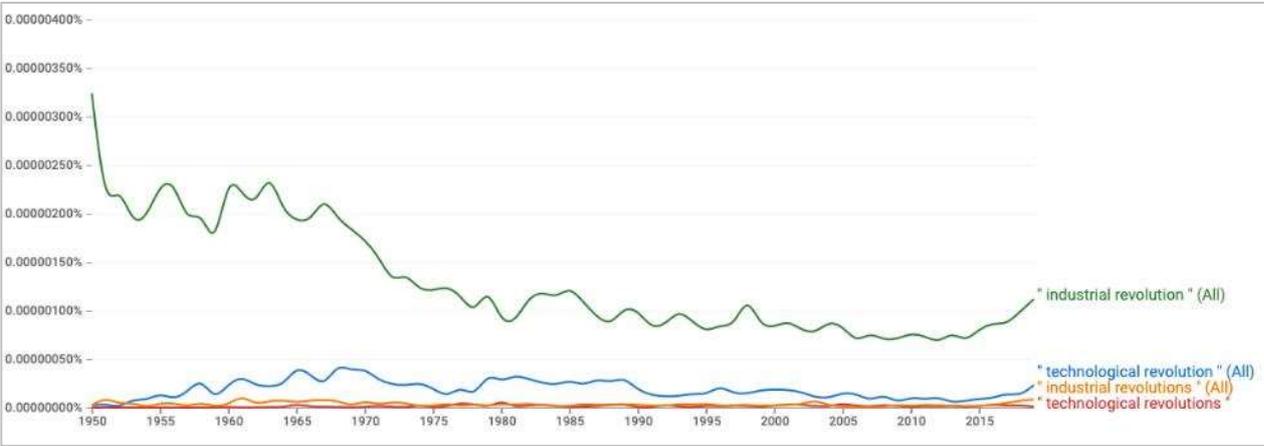


Figure A.3.3. Use of the phrases ‘technological revolution/s’ and ‘industrial revolution/s’ over time, detail, 1950-2019



Finally, we compared ‘industry 4.0’ (non-case sensitive) and ‘Industrie 4.0’ (non-case sensitive search, but only capitalised results due to the German conventions). Both appear in the English corpus in 2010, ‘Industrie 4.0’ making an appearance in the German corpus the year before – interestingly, before the use at the Hannover Fair in 2011 generally cited as the origin of the phrase. While ‘industrial revolution’ in the singular grows slightly in popularity, **the English version of ‘Industry 4.0’ rapidly and significantly overtakes it in usage, and both English and German variants soar over the plurals of ‘technological revolutions’ and ‘industrial revolutions’ in popularity.**

Figure A.3.4. Use of the phrases 'technological revolution', 'industrial revolution', 'industry 4.0' and 'Industrie 4.0' over time, 2000-2019

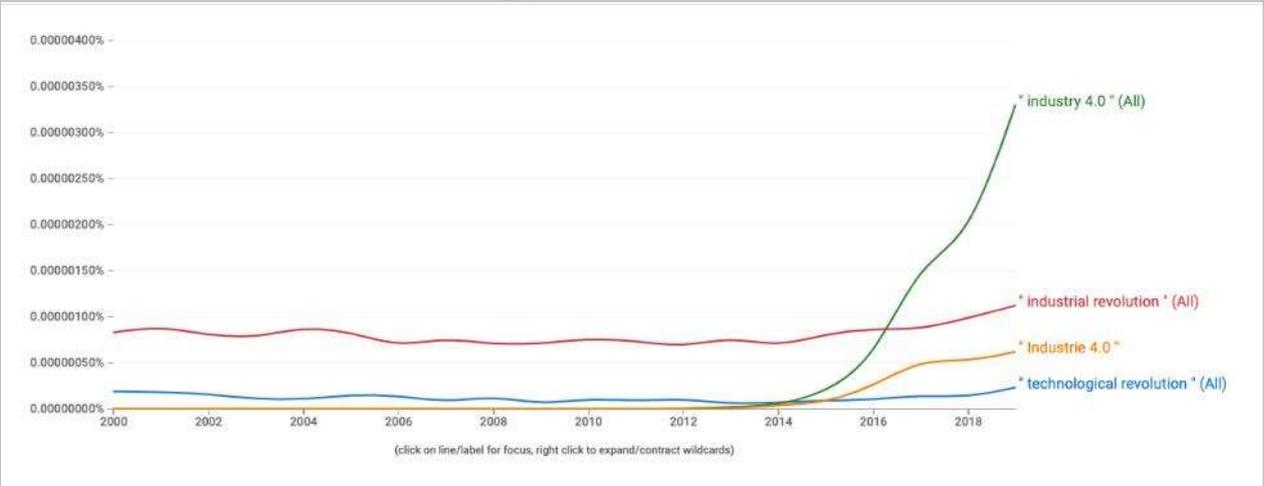
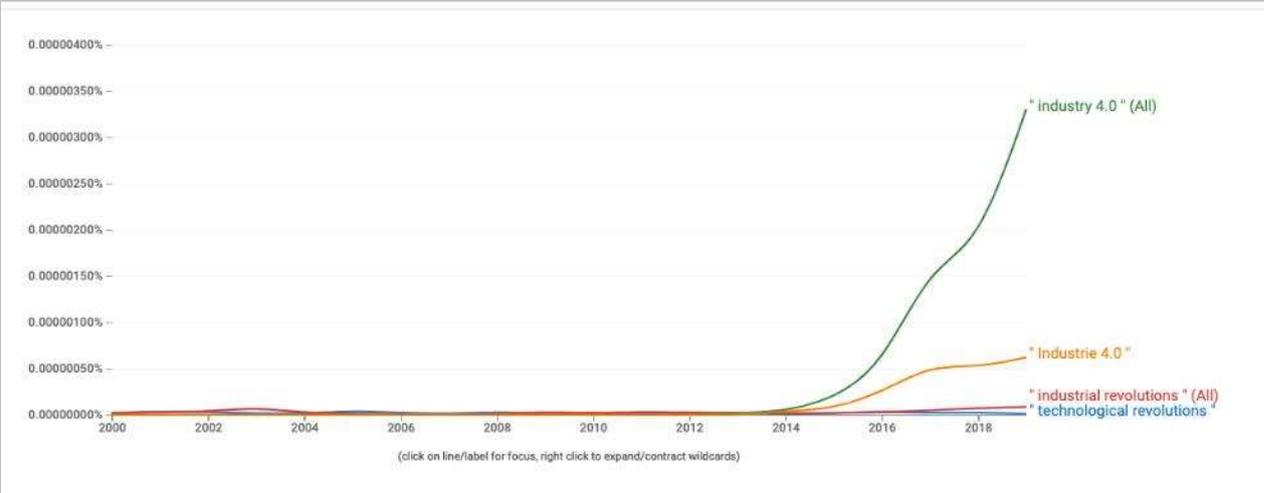


Figure A.3.5. Use of the phrases 'technological revolutions', 'industrial revolutions', 'industry 4.0' and 'Industrie 4.0' over time, 2000-2019



A.4 Google Books

As noted above, the Ngram generator suggests periodisations below each Ngram and ranks the 'most relevant' publications for each search term. This periodisation is not only not useful in the dates set – for example, one period might be 1 Jan 1981-31 Dec 2015, another, in the same search, 1 Jan 1966-31 Dec 1969 – but also does not always replicate when the same search is performed twice. Furthermore, it turns out that these periods can be replicated with a Google Books search for those dates, but applying the 'with all of the words' modifier, not the 'with the exact phrase', despite the correct use of the Boolean search limiters in the Ngram search bar. Furthermore, if one attempts to set the periodisations manually via Ngram, which is supposedly a feature, the search crashes.

Therefore, to look at what types of works in the corpus were featuring in the Ngram searches, we manually set periodisations for our search terms in Google Books, and looked at results using both the 'with all the words' and 'exact phrase' modifiers. We examined periodisations that reflected the peaks and troughs of usage in the Ngrams, and those that looked at the results more or less by decade, but accounting for certain historical events (such as the global economic crash of 2008).

As discussed in the section on Ngrams, experiential knowledge of a field reveals that these searches tell us only a little, and may hide as much as they show. Again, we had a difficult time replicating the searches on repeat, and for different users, even when performing the search signed out of Google. In searching for 'technological revolutions', for example, Freeman's work appeared on one day and disappeared the next. Perez' book *Technological Revolutions and Financial Capital* (Elgar, 2002), and chapters from that book, rank highly for that decade; in the years that follow, however, some other publications rank highly simply because that book is cited a number of times in their bibliographies (see, for example, Bonvillian and Weiss 2015; Williams 2012; and Hanna 2013 in the ranking below). Schwab's *Fourth Industrial Revolution* ranks highly for 'industrial revolution', 'technological revolutions' and 'Industry 4.0'. **So to a degree, such results can and do confirm the relevance of some of those authors originally shortlisted for inclusion in the literature review. But more on that list do not show up in the Google Books search for any of these terms, and this does not map onto whether their significant works are academic or popular.** Other entries that do make the rankings flag up its flaws: the volume edited by Heertje and Perlman (1990) is only included due to the exact phrase 'technological revolutions' used in a short comment on one essay, according to the search, yet the book is filled with neo-Schumpeterian analysis of technological revolutions. The book includes a chapter by Freeman on Schumpeter's 'Business Cycles Revisited'; by Lazonick on 'Three Industrial Revolutions'; and on the various 'Technological Winds of Creation and Destruction' by Zajac. This just shows how limited word searches for specific terms are; **one needs to know the field in order to research the field, and numbers don't tell much of the story, just illustrate some general trends.**

Perhaps such a search is of most use to convey a flavour of what types of publication rank most relevant for the different periods, as this could be seen to change over time for all terms. It does also confirm that at least some of the use reflected in the Ngram relates to the study of technological/industrial change by revolution. But that is about the extent of what can infer.

Here we include the search results for 'technological revolutions', showing the shift from government publication in the 1960s, the rise of works on innovation, and the most recent focus on

examinations of the capitalist economic structure. Note that Cook (1995) appears multiple times, due to two of the limitations of the Google Books search described above: republication and plain old error. Note also that these are periodisations, with citations as per Google and not included in our own bibliography except where referred to directly elsewhere. We have opted to list by title first rather than author, in order to show the trends and diversity in the type of publications featured.

Figure A.4 Top 10 Advanced Search 'exact phrase' Google Books results for 'technological revolutions', 1950-2019.

<p><u>Jan 2016-December 2019</u></p> <ol style="list-style-type: none"> 1) Being and the Screen: How the Digital Changes Perception. Vial, Stéphane. (2019) MIT Press. 2) The Technology Trap: Capital, Labor, and Power in the Age of Automation. Carl Benedikt Frey (2019) Princeton University Press. 3) 'Empirical Links Between Kondratiev Cycles and Technological Revolutions', Papageorgious, Aris, in Public Sector Economics & Development. İçke, Basak Turn et al., (2018) Ijopec Publication. 4) Connectivity in Antiquity: Globalization as a Long-Term Historical Process. Oystein S. LaBianca, Sandra Arnold Scham (2016) Taylor & Francis. 5) Proceedings of the 12th International Conference on Cyber Warfare and Security, Wright State University with the Air Force Institute of Technology, 2-3 March 2017 6) Doing Capitalism in the Innovation Economy: Reconfiguring the Three-Player Game Between Markets, Speculators and the State. Janeway, William H. (2018). Cambridge University Press. 7) Manpower Policies for the Use of Science and Technology in Development, Pergamon Policy Studies on Socio-Economic Development. Charles V. Kidd. (2017). Elsevier Science 8) A History of Western Thought: From Ancient Greece to the Twentieth Century. Nils Gilje, Gunnar Skirbekk (2013). Taylor & Francis. 9) Nanotechnology and Global Sustainability. Donald Maclurcan and Natalia Radywyl, eds. (2012). CRC Press. 10) The Fourth Industrial Revolution. Klaus Schwab (2017). Penguin Books
<p><u>Jan 2008-December 2015</u></p> <ol style="list-style-type: none"> 1) Technological Innovation in Legacy Sectors. William Bonvillian, Charles Weiss. (2015). Oxford University Press. 2) 'The Structure of Technological Revolutions and the Gutenberg Myth' by Scott D.N. Cook in New Directions in the Philosophy of Technology (listed at least twice in Google Books, here as 2013 – but was actually published in 1995), Joseph C. Pitt, ed. Springer Netherlands. 3) 'Science & Technology and Modernization' by Jing Jin in Civilisation and Modernization – Proceedings of the Russian-Chinese Conference 2012. Chuanqi He, Nikolay Lapin, eds. (2014) World Scientific Publishing Company.

- 4) The Nature of Technological Knowledge. Are Models of Scientific Change Relevant? Rachel Laudan, ed. (2013) Springer Netherlands.
- 5) The Economics of Cloud Computing: An Overview For Decision Makers Bill Williams (2012) Pearson Education.
- 6) Transforming Government and Building the Information Society: Challenges and Opportunities for the Developing World Nagy. K. Hanna. (2013) Springer: Innovation, Technology, and Knowledge Management Series.
- 7) Network Society and Future Scenarios for a Collaborative Economy Vasilis Kostakis, Michel Bauwens. (2014) Palgrave Macmillan.
- 8) 'Technological Revolutions and the Role of Government in Unleashing Golden Ages', Perez, Carlota in Kondratieff Waves: Dimensions and Prospects at the Dawn of the 21st Century (2012), Grinin, Leonid et al. , eds. Volgograd: Uchitel Publishing House
- 9) Handbook of Research on Digital Libraries: Design, Development, and Impact Yin-Leng Theng, eds. (2009) IGI Global.
- 10) 'Integrated marketing communications: From media channels to digital connectivity' Mulhern, Frank, in The Evolution of Integrated Marketing Communications: The Customer-driven Marketplace, Patti, Charles H. and Kitchen, Philip J. eds., (2011) Taylor & Francis.

Jan 1996-Dec 2007 (set to pre-crash date)

- 1) Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Carlota Perez (2002) Edward Elgar Publishing.
- 2) As above
- 3) As above [although on a different date this position was assumed by As Time Goes By, Freeman and Louca 2001]
- 4) Technological Revolutions in Europe: Historical Perspectives Maxine Berg and Kristine Bruland, eds. (2009) Edward Elgar.
- 5) 'The Structure of Technological Revolutions and the Gutenberg Myth' by Scott D.N. Cook [Note: this is included in a different edited volume that also appears in the year it was first published 1995 and again in 2013] in Internet Dreams: Archetypes, Myths, and Metaphors, Mark Stefik (ed.), (2007) MIT Press.
- 6) Science and Technology in World History: An Introduction James Edward McClellan and Harold Dorn (2006) Johns Hopkins University Press
- 7) Technological Trajectories and the Human Environment Jesse H. Ausubel and H. Dale Langford, eds. (1997) National Academy of Engineering,
- 8) Technological Communities and Networks: Triggers and Drivers for Innovation Dimitris Assimakopoulos. (2007) Taylor & Francis
- 9) 'The Information Technology Revolution: A New Techno-Economic Paradigm' Spas Spassov in Bulgarian Studies in the Philosophy of Science Dimitri Ginev, eds. (2003) Dordrecht/Boston/London. Kluwer Academic Publishers.
- 10) Economics of Structural and Technological Change Gilberto Antonelli and Nicola de Liso, eds. (1997) London and New York: Routledge.

Jan 1976-Dec 1995 (set to cover the peak shown in the Ngrams across the '80s; a search of '85-'96 brings up an almost identical list)

- 1) *The Structure of Technological Revolutions: An Empirical Study of the Development of III-V Compound Semiconductor Technology* Michael A. Rappa (1988) University of Minnesota.
- 2) 'The Structure of Technological Revolutions and the Gutenberg Myth' by Scott D.N. Cook in *New Directions in the Philosophy of Technology* C. Pitt, ed. (1995 [note included elsewhere – erroneously - as 2013) Joseph Kluwer Academic Publishers/Springer
- 3) 'Technology, Power and Truth' Marx. W. Wartofsky in *Democracy in a Technological Society* Langdon Winner, ed. (1992) Kluwer Academic Publishers/Springer.
- 4) *The Nature of Technological Knowledge. Are Models of Scientific Change Relevant?* Rachel Laudan, ed. (1984 –listed erroneously elsewhere as 2013) Kluwer Academic Publishing / Springer Netherlands.
- 5) *Civilization and Capitalism, 15th-18th Century, Vol. I: The Structure of Everyday Life* Fernand Braudel (1992, Siân Reynolds translation). University of California Press.
- 6) 'Provide for a Research Program to Examine and Enhance Agricultural Production and Food Processing Systems'. Hearing Before the Subcommittee on Livestock, Dairy, and Poultry of the Committee on Agriculture, House of Representatives, One-Hundredth Congress, Second Session, on H.R. 3735, March 24, 1988.
- 7) *Technological Transition in Cartography* Mark S. Monmonier (1985) University of Wisconsin Press.
- 8) *Terminal Identity: The Virtual Subject in Postmodern Science Fiction* Scott Bukatman (1993) Duke University Press
- 9) *Evolving Technology and Market Structure: Studies in Schumpeterian Economics* Arnold Heertje and Mark Perlman, eds. (1990) Ann Arbor: University of Michigan Press.
- 10) *Scientific-technological Revolution: Social Aspects*. Sage Publications for the International Sociological Association. Ralf Dahrendorf, Ramkrishna Mukherjee (1977 – but these are papers 'presented in the first plenary session of the Eighth World Congress of Sociology, held in Toronto in August 1974').

Jan 1950-Dec 1975

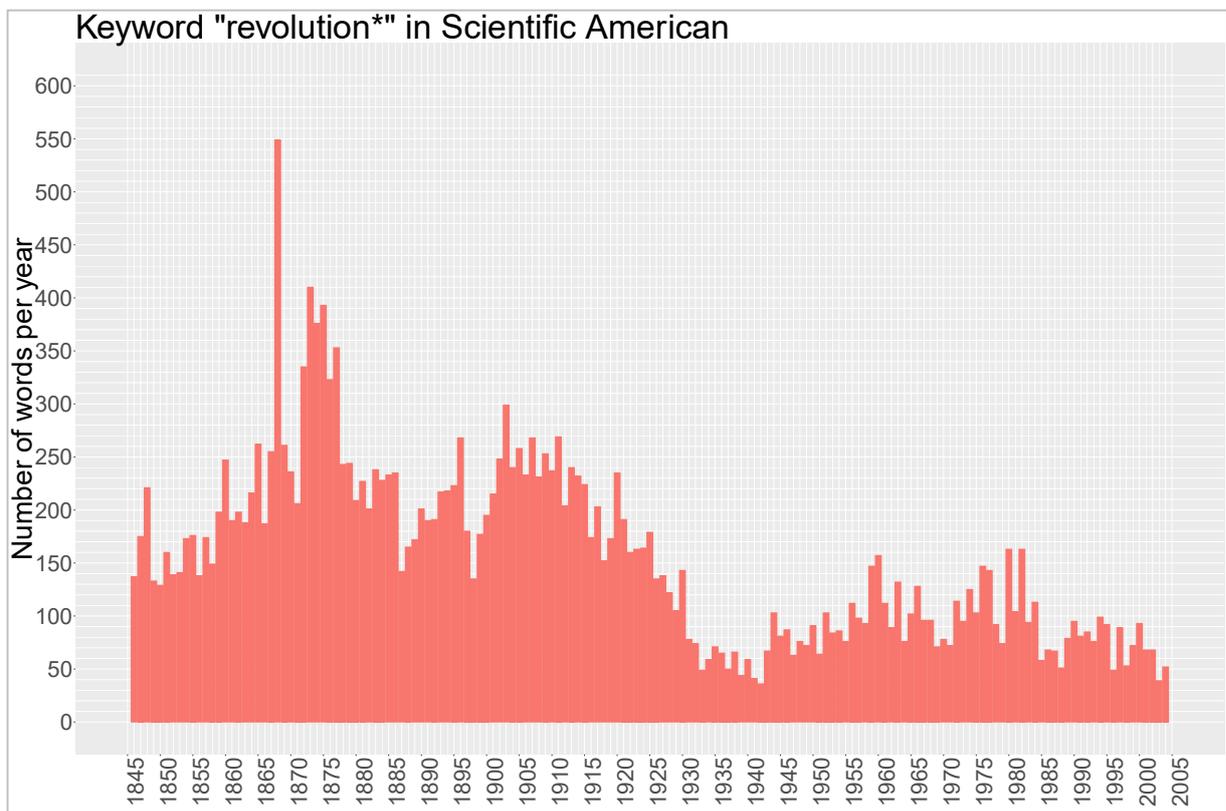
- 1) *Educational Implications of Technological Change, Technology and the American Economy Report, Appendix Volume IV*, (February 1966) National Commission on Technology, Automation, and Economic Progress.
- 2) *The Department of State Bulletin, Volume 26*, (1952) Office of Public Communication, Bureau of Public Affairs, US Department of State.
- 3) *The Sociology of the Third World: Disparity and Involvement* J. E. Goldthorpe (1975) Cambridge University Press
- 4) *The Spirit of India: Volumes Presented to Shrimati Indira Gandhi by the Indira Gandhi Abhinandan Samiti. Volume 2* (1975) Asia Publishing House.

- 5) 'Socio-technological Systems Engineering for Developing Countries', Class Notes for Course 511, Introduction to Systems Engineering, January 1974 Term. The role of technology, Part 1, Donald R. Drew (1974) Asian Institute of Technology.
- 6) Michigan Business Review Volumes 5-6 (1953) Ann Arbor: University of Michigan.
- 7) The Development, Economics, and Impact of Technological Change in Transportation: The Case of Containerization · Volume 1. Theodore O. Wallin (1974) Cornell University.
- 8) The Civilizational Process, Darcy Ribeiro (1971) Harper & Row.
- 9) 'Christians in the Technical and Social Revolutions of Our Time', World Conference on Church and Society, Geneva, July 12-26, 1966. (1967) World Council of Churches.
- 10) World Marxist Review, Volume 19, Issues 1-6 (1968)

A.5 Scientific American

Dr Frédérique Bone and colleagues from the Deep Transitions project at SPRU, University of Sussex are currently looking at the corpus of Scientific American, with data available from 1845 to 2005. Whilst the phrase 'technological revolution' was not examined, data was available for the words 'revolution', 'revolutionize', and 'revolution*', where the latter includes all words which use that root. Of course, although the popular magazine focuses on science and technology, we cannot infer from the data in what context those words are being used. And the researchers are keen to point out that fluctuations are in part due to changes in the length of the journal and the number of issues per year. However, it is notable that **peaks in use since the 1940s occur in the same periods as in the NGRAMS for 'technological revolution*' and 'industrial revolution*'**: the early 1960s, 1975-85, and the early '90s (the latest peak, from about 2018, is not covered).

Figure A.5. Keyword 'revolution' in Scientific American



A.6 Google Scholar

At the time of our last search, searching publications from 1800 - 2019, 'technological revolutions' returned 15,700 results, with 101 results for the title search. The singular, 'technological revolution' returned 101,000 results, with 585 results for a title search. (All search figures listed here exclude patents and citations, which can be included in a Google Scholar search).

As discussed in the Approach section of the paper, and in the discussion on Ngrams above, our hypothesis was that the plural would return more relevant results to the topic of our paper than the singular – and this did indeed prove to be the case. **To illustrate the limitations and usefulness of the type of 'systematic search' of social science theory performed in the early phases of our task, as discussed in our Approach, we list below the top ten results 'by relevance' returned for 'technological revolutions', with a brief summary of the relevance of their contents to our work.** Note that Google Scholar provides no straightforward way to rank by citation in such a search, although research has shown that the database returns papers with 'a strong correlation between a document's citations and its position in the search results, $r = -0.67$ ' (Martin-Martin et al., 2017).

While only one of these papers made the shortlist for discussion in the main body of the paper, ranked at number 11 in relevance was the European Trade Union Institute (ETUI) Foresight Brief on 'Technological Revolutions and societal transitions' (Valenduc, 2018), which covers similar ground to our paper: looking briefly at the theories of Kondratiev, Mandel, Nagel before delving into the Schumpeterian and then neo-Schumpeterian perspectives, going deeply into the work of Perez and Freeman, touching very lightly on Brynjolfsson and McAfee, Schwab and Rifkin before concluding that the Perez periodisation is the correct one - perhaps not surprisingly, given that of the 19 works included in its bibliography, four are by Perez, two Freeman and one Jacobs and Mazzucato.

But Edward L. Ayers' 2002 paper, 'Technological Revolutions I Have Known', focused on upgrading technology in the academy and therefore itself of no relevance in itself to our paper, reminded us that we had forgotten to consider the work of economist, physicist and long-wave scholar Robert U. Ayers. **This is part of the story behind so-called systematic reviews, then – one is trawling for evidence, and what comes up is not always so easy to document with numbers.**

A less positive aspect are those that papers appear promising by title, are included in overall counts, and yet, on closer inspection, are of no relevance to the topic. Performing a search of 'technological revolutions' in combination with 'measure*' (see notes on modifying terms and definitions in Section A.2) brought up the article 'How do you measure a 'technological revolution?'' (Corrado and Hulten, 2010). Yet – and with no offense to the authors, who intended something else entirely by the title – this does not discuss how one might periodise technological change, but is rather the proposition of a new set of measurements for technological change based on business inputs and intangible capital investment instead of old, old-fashioned growth accounting. The 'technological revolution' under discussion remains undefined.

We followed a similar process for 'industrial revolution/s'. As hypothesised, the singular, 'industrial revolution', returned the most results (799,000), but of the top twenty returned documents, the majority dealt with what is considered the first – or only – 'Industrial Revolution', as per our hypothesis; one with what some scholars recognise as the 'Second' (in this case 1870-1914); and five with the impact of ICT in the present. The plural, however, with a total of 17,700 results (115 in

the title search), returned results directly relevant to the literature review. Most highly cited (with a count of 2321, by about 2000 on the other papers) was Freeman and Louça (2001), discussed at length in the main body of this paper. The influential business historian Thomas McCraw (1998) and economic historian Patrick O'Brien (1994) both make the top twenty, as does the 1956 paper on 'Industrial Growth and Industrial Revolutions' by the industrial historian D.C. Coleman, which, some seventy years before the outpouring of scholarly work asserting a fourth or fifth industrial revolution based on little more than World Economic Forum hearsay, critically and painstakingly picks apart the notion. Not only, **Coleman observes, 'in the writings of economic historians, revolutions abound', but 'largely an offspring of the writings of engineers, mathematicians and others normally unacquainted with the works of economic historians ... this variety of uses of the term 'industrial revolution' can scarcely fail to be confusing.'** (p.1). Unfortunately, other, far more recent papers that seemed promising by title or abstract, on further investigation offered very little in the way of critical analysis of the different definitions of revolutions, picking and choosing periodisations and revolutionary characteristics asserted by different scholars to fit their broader arguments (see, for example, Pozdnyakova et al., 2018; Melnyk et al., 2019).

Figure A.6. Top ten "relevant" search results for the phrase "technological revolutions" in Google Scholar

<p>1) Caselli, F. (1999). 'Technological Revolutions.' <i>American Economic Review</i>, 89 (1): 78-102. (citations: 789)</p> <p>- Does not interrogate the term but uses it for inventions, such as the steam engine, in a paper that primarily studies skilling/deskilling and capital-labour ratios since the 1970s.</p>
<p>2) Perez, C. (2003). <i>Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages</i>. Elgar. (citations: 3071)</p> <p>- By far the most highly cited document returned for this search, almost 2000 more than the next document, which was also a Perez article – Perez 2010 (see #4).</p>
<p>3) Pástor, L. and Veronesi, P. (2009). 'Technological Revolutions and Stock Prices.' <i>American Economic Review</i>, 99 (4): 1451-83. (citations: 437)</p> <p>- although citing, in passing, the work of Malkiel (1999), Perez (2002), Shiller (2000) and others, they do not define revolutions other than to say that they are focusing on 'the railroads' and 'the internet' as technological revolutions in developing their notion of changing uncertainty in a general equilibrium model.</p>
<p>4) Perez, C. (2010). 'Technological revolutions and techno-economic paradigms', <i>Cambridge Journal of Economics</i>, Vol 34, Issue 1, January 2010, 185-202. (citations: 1083)</p>
<p>5) Perez, C. (2004). 'Technological revolutions, paradigm shifts and socio-institutional change', in <i>Globalization, Economic Development and Inequality: An Alternative Perspective</i>, Erik S. Reinert ed. (citations: 339)</p>
<p>6) Atkeson, A. and Kehoe, P.J. (2007.) 'Modeling the Transition to a New Economy: Lessons from Two Technological Revolutions.' <i>American Economic Review</i>, 97 (1): 64-88. (citations: 182)</p> <p>- uses the 'three revolutions' model of Gordon et al., focused on the 'large number of technologies invented' in the late 18th century (first revolution) and 1860-90 (second revolution)</p>

in building a model to analyse the diffusion of technology in the 'more recent Information Technology (IT) Revolution.'

7) Berg, M. and Bruland, K. (eds.) *Technological Revolutions in Europe: Historical Perspectives*, 1998. Edward Elgar Publishing. (citations: 57)

- With chapters by the 'leading historians of technology': E. Anderson, M. Berg, K. Bruland, F. Caron, C. Evans, R. Fox, T. Griffiths, P. Hunt, M.C. Jacob, A.O. Johansson, B.Z. Khan, D.S. Landes, C. MacLeod, J. Mokyr, P. O'Brien, G. Rydén, F. Sejersted, K.L. Sokoloff, N. von Tunzelmann. Some of these authors were already on our shortlist; this early search reminded us to add those we hadn't yet included.

8) Bostrom, N. (2006) 'Technological Revolutions: Ethics And Policy In The Dark 1', in *Nanoscale: Issues and Perspectives for the Nano Century*, Cameron, N.M.de S. and Mitchell M.W. (eds.), John Wiley 2007, pp. 129-152. (big bang model, though not called that in the paper). (citations: 90)

9) Jovanovic, B. and Rousseau, P.L. 'Two Technological Revolutions', *Journal of the European Economic Association*, Volume 1, Issue 2-3, 1 May 2003, Pages 419–428. (citations: 42)
- Discusses the relative value of the IPOs of the 'Electricity/Internal Combustion revolution' (1890-1930) vs the 'IT Revolution' (1971-2001) without explaining their choice of periodisation. Cited by 42.

10) Cohen, A.M. (2006) *Shakespeare and Technology: Dramatizing Early Modern Technological Revolutions* Basingstoke: Palgrave Macmillan. (citations: 53)
- a nice example of the diversity of work, this considers representations of new technologies-as-inventions in the work of Shakespeare.

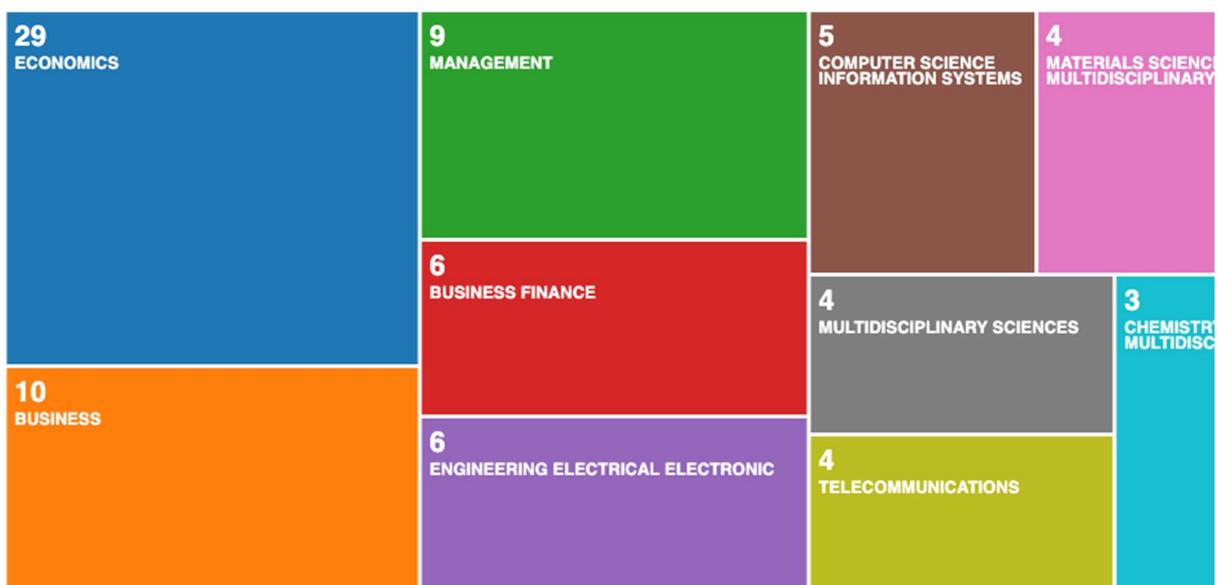
A.7 Web of Science, other databases and individual journals

Extensive in content and featuring detailed ‘citation report’ features, the Web of Science Core Collection (WoS) database is frequently used as a database for systematic searches across the academy, and has been mined by those attempting to define and organise work on related topics to our paper (see, for example, Martin, 2012; Kamble et al., 2018). However, at least in our experience of fulfilling Task 7.1, using the WoS solely – or indeed any single source – would result in a distorted picture of the debate under review.

Given our earlier results with Google Books and Scholar, we chose to use the plurals, ‘technological revolutions’ and ‘industrial revolutions’, as our key terms, searching for these phrases alone and in pairs with the various modifying keywords already discussed, and using both the topic search (TS) and title search (TI) functions of the WoS platform. We searched only articles, books and book chapters, in the English language, from 1900-2019.

As with Google Scholar, to illustrate the process we shall focus our discussion here on a selection of the results returned for ‘technological revolutions’ in a topic search. Only 93 results were returned in total, across multiple disciplines; Figure 5 shows the range, provided by the WoS ‘Analyse Results’ tool. Within this search the top ten by citation include work on systems vaccinology (Nakaya et al., 2012), medical imaging (Ratib et al., 2003) and the homeostasis of body weight regulation (Prentice et al., 2004). This range can be controlled to an extent by de-selecting the various natural science-oriented citation indexes that comprise the core collection, and then further refined by deselecting the WoS-assigned categories. However, **at this point any cross-disciplinary systematic search becomes subjective, relying upon the prior knowledge and judgement of the researcher – and the accuracy of categorisation.** ‘Pediatrics’ might be an obvious category to reject, but what of ‘Management’?

Figure A.7.1. Range of disciplines returned in search for ‘technological revolutions’



Source: Web of Science, Clarivate Analytics (<https://www.webofknowledge.com>).

Selecting the categories of: Economics, Business, History, Management, Business Finance, History of Social Sciences, Philosophy, Multidisciplinary Sciences, Sociology, Political Science, Development Studies, Humanities Multidisciplinary, Social Sciences Interdisciplinary, Anthropology, History Philosophy of Science, Industrial Relations Labor, and Social Sciences Mathematical Methods, returned 77 results in total. **Even with these modifications, the most highly ranked by citation remained an article on 3D printing** (Rayna and Striukova 2016); the fourth on container shipping (Ducruet and Notteboom 2012): the same as without category refinement. **Of the remaining eight in the top ten by citation** (listed below), **five correlate with the top ten ‘most relevant’ results returned by Google Scholar**: Caselli 1999, Perez 2004 and 2010, Pastor et al., 2009 and Atkeson and Kehoe (2007). Note, however, that **their citation counts here are far less, suggesting that using the WoS only as an indication of highly cited works may be misleading**. Perez 2009 is included in the WoS top ten and not in Google Scholar, but Perez 2002 is not included; it does appear in the WoS database, but is erroneously dated as 2011, and the author is listed as ‘Perez, C.’, while the nine articles by Perez listed in the database are under ‘Perez, Carlota’. Furthermore, chapters that are actually from Perez (2002) show up in the search for ‘technological revolutions’ when using the ‘Analyse Results’ function, under book chapters – but are credited to Freeman, who in fact wrote the preface only. We use the author of this paper like the example here not to gripe, but purely to illustrate the limitations of relying solely on databases in order to carry out a review – and the value of knowledge that comes from familiarity.

Where the limitations of WoS are most apparent are in the downplaying or outright omission of key authors in the debate. This is due to a variety of reasons: the emphasis of the article is not considered a fit the ‘technological revolutions’ or ‘industrial revolutions’ search parameters; the article is not highly cited within the indexes used by the WoS; the publishing journal is not highly weighted; the author primarily publishes outside of publications considered to be ‘academic scholarship’. This is well-illustrated with an author search. Looking at the data for the contemporary scholars on our original shortlist, Brynjolfsson comes out the most highly cited (sum of times cited 3220; citing articles 2990; average citations per year 218.47). Frey (citing articles 863) and Perez (citing articles 373) both have far lower citation records than on Google Scholar. Gordon is accredited with 259 citing articles, but although 28 publications are listed under his name (and some of these are actually by another Robert J.), his most influential work in the revolutions debate, Gordon 2012, is not included – presumably because it was published as a working and then policy paper, and not in a scholarly journal.

Meanwhile, **although a search for the term ‘Industry 4.0’ returned 1124 papers and ‘Fourth Industrial Revolution’ 445, Schwab, who popularised their use, has only five listings on the WoS**, the most popular on global corporate citizenship (Schwab 2008), for which 57 of his 59 total citations are credited. As part of our research, we looked at the **Amazon rankings** for the key works of the authors featured in the paper. Other than for the author and publisher, these rankings are only a snapshot in time; in 2018, Amazon cancelled access for external sites that permitted the tracking of these rankings over time. However, throughout the period of our research, Schwab’s *The Fourth Industrial Revolution* (2017) was (and remains) consistently in the top hundred, if not top ten, in numerous Amazon.com and Amazon.co.uk business, economics and politics categories in all formats (hardback, paperback, Kindle and audiobook). At our last official check in January 2021, it was still ranked #1 in International Finance on Amazon.co.uk. **Given that – we believe – one, if not**

the primary aim of scholarship in our field is to inform policy and the public conception of what might be, to survey works in databases that prioritise 'scholarship' without looking at those works that have so strongly influenced the public and political debate is problematic.

Other databases used in our mapping exercise included **EconLit**, which gave 81 results for 'technological revolutions (all text, 1987 – 2019; 1987 is the earliest date in the database), with Perez (2010), Pastor and Veronesi (2009), Caselli (1999) and Atkeson and Kehoe (2007) again in the top ten results by relevance; and 84 results for 'industrial revolutions', with the focus split on growth theory, historical studies of either the first or 'three revolutions', or 'the fourth industrial revolution' in the Schwabian conception. Given the limited dates covered by this database, part of our research included an analysis of content by decade. **Much like the works included in Google Books, there is a discernible change over the years** – and this is for all papers included in these search terms and not the much more limited number that study the periodisation of history in a manner covered by our paper. It is interesting to see, however, how **the focus of those looking at technological/industrial change and its relationship to economics shifts**. Articles from the late 80s and early 90s are likely to have a focus on theories of technical change, growth and development. By the mid-90s, there are more with a specific focus on ICT-related technologies and the assertion that the world is in a new period of technological development. 'Global' and 'globalisation' become common title words by the turn of the millennium; a decade later, 'green' topics begin to rise in popularity, along with a focus on specific industries or nations and their development, and references to 'the information age' and 'the knowledge economy'. By 2015 there is a definite emphasis on 'the future of work' and other labour economics issues, and the rise of 'Industry 4.0'.

Scopus has several useful search features, including the ability to rank by citation and by relevance, and a list of authors with the most papers included for any search term. Perez is top of that list for the term 'technological revolutions', and the database includes one of her earliest papers on the topic, 'Long Waves and Changes in Socioeconomic Organisation' (1985), not included elsewhere. The patterns we discerned here were similar to those described above for both 'technological revolutions' and 'industrial revolutions', (and many of the same papers showed up in the most cited/most relevant). In general, most papers for the latter were not relevant, with an emphasis on industrial revolutions as a stage of development (often for specific nations) rather than a focus on repeating patterns; where relevant, the predominant dating until the last five years or so was an unexamined assumption of three revolutions. For the former, the emphasis shifted from waves to innovation – and then, for both, **over the past few years, a huge surge in papers writing of 'the Fourth Industrial Revolution' or 'Industry 4.0' as unexamined or barely examined fact rather than theory, which held even with work purporting to be discussing the conceptual framework of the term** (see, for example, Kaya 2019, which tentatively mentions that Industry 4.0 'does not have a generally accepted definition by academics' (p.18) yet still repeats the standard Industry 4.0 assertions, including the oft-used diagrams from the German Industrie 4.0 Working Group paper (Kagermann et al., 2013).

We also cross-checked the findings of these databases with those of the **Economics Research Network (ERN)**, **EconPapers** and the **National Bureau of Economic Research (NBER) Working Papers** database.

This then led us to the last stage of the mapping exercise: **a deep dive into the indexes of individual journals**. These came from across multiple disciplines, as Figure A.7 illustrates and as already discussed above and in the Approach section of the paper. There is little to discuss here that is not covered in the critical review of the paper. However, it is perhaps worth noting that the most fruitful sources of work on the topic of our paper were the **future forecasting journals**, and in particular Technological Forecasting and Social Change (Elsevier, established in 1969), and Futures (Elsevier, established 1968). As with the databases (and the Ngrams for the same period), **there is a clear shift in focus of articles on technological/industrial revolutions in these journals**, with an emphasis on long waves and the diffusion of innovation discernible in the 1980s and 1990s, now all but replaced – or at the very least swamped – by article after article by young, primarily non-Western researchers who premise their work on the existence of ‘the 4th industrial revolution’ as a given. This means that in the past 25 years, we have dropped a revolution – most papers in the previous surge of studies assuming five revolutions, taking Kondratiev’s calculations as their basis even if they weren’t K-wave adherents. The present ‘wave’ of scholars are clearly on board with the Industry/ie 4.0 four.

Figure A.7.2. Ten most highly cited articles in the WoS returned for the search ‘technological revolutions’ using relevant categories

1) Rayna, T. and Striukova, L. (2016) ‘From rapid prototyping to home fabrication: How 3D printing is changing business model innovation’, Technological Forecasting And Social Changezz Volume: 102 Pages: 214-224 DOI: 10.1016/j.techfore.2015.07.023 (citations: 226)
2) Caselli, F. (1999) ‘Technological revolutions’ American Economic Review Volume: 89 Issue: 1 Pages: 78-102 DOI: 10.1257/aer.89.1.78 (citations: 214)
3) Perez, C. (2010) ‘Technological revolutions and techno-economic paradigms’ Cambridge Journal Of Economics Volume: 34 Issue: 1 Pages: 185-202 DOI: 10.1093/cje/bep051 (citations: 177)
4) Ducruet, C. and Notteboom, T. (2012) ‘The worldwide maritime network of container shipping: spatial structure and regional dynamics’, Global Networks-A Journal Of Transnational Affairs, Volume: 12 Issue: 3 Pages: 395-423 DOI: 10.1111/j.1471-0374.2011.00355.x (citations: 150)
5) Pastor, L. and Veronesi, P. (2009) ‘Technological Revolutions and Stock Prices’, American Economic Review, Volume: 99 Issue: 4 Pages: 1451-1483 DOI: 10.1257/aer.99.4.1451 (citations: 106)
6) Perez, C. (2009) ‘The double bubble at the turn of the century: technological roots and structural implications’, Cambridge Journal Of Economics Volume: 33 Issue: 4 Pages: 779-805 DOI: 10.1093/cje/bep028 (citations: 82)
7) Kuznetsov, B.L.; Kuznetsova, S.B. (2016) ‘Technological Management in the Conditions of Scientific-Technological Revolutions of the XXIst Century’ Upravlenets-The Manager Issue: 3 Pages: 2-7 (citations: 71)
8) Perez, C. (2004) ‘Technological revolutions, paradigm shifts and socio-institutional change’, Globalization, Economic Development And Inequality: An Alternative Perspective Book Series:

New Horizons in Institutional and Evolutionary Economics Pages: 217-242 Published: 2004(citations: 54)

9) Atkeson, A. and Kehoe, P.J. (2007) 'Modeling the transition to a new economy: Lessons from two technological revolutions', American Economic Review Volume: 97 Issue: 1 Pages: 64-88 (citations: 49)

10) Beaudry, P., Doms, M. and Lewis, E. (2010) 'Should the Personal Computer Be Considered a Technological Revolution? Evidence from US Metropolitan Areas' Journal Of Political Economy Volume: 118 Issue: 5 Pages: 988-1036 (citations: 48)

Source: Web of Science, Clarivate Analytics (<https://www.webofknowledge.com>). Citations are per the WoS and not replicated in our Bibliography unless referred to elsewhere in the text.