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2019

Document Version:
Other version

Link to publication

Citation for published version (APA):
Taalbi, J. (2019). *Innovation waves and technological transitions: Sweden, 1909-2016*. (Lund Papers in Economic History. General Issues; No. 2019:196).

Total number of authors:
1

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Lund Papers in Economic History

No. 196, 2019 *General Issues*

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Lund Papers in Economic History
ISRN LUSADG-SAEH-P--19/196--SE+31

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Innovation waves and technological transitions. Sweden, 1909-2016 *

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Abstract

There are important unresolved questions about long-term trends of innovation activity and the nature of the interplay between innovation and economic development and transformation. This study explores the promise of a literature-based innovation output indicator, constructed for the Swedish engineering industry, 1909-2016. The findings suggest a long-run increasing trend in innovations per capita. Meanwhile, product innovations have also become more complex and it is suggested that crude innovation counts underestimate the long-run innovation performance. In order to analyse innovation and economic development across different frequencies, the study uses a wavelet decomposition approach. The results suggest that innovation activity has surged in periods of intense industry rationalization and structural crisis (1930s, 1970s and 2010s) and that such pulses were intimately connected to the second and third industrial revolutions.

JEL: N13 O31 O14.

Keywords: Innovation, Wavelet analysis, Technological systems

1 Introduction

Technological innovation is widely viewed as a necessary, although not in itself sufficient, facet of economic development and sustainable transitions towards low-carbon economies. High anticipations have come with 3D-printers, robotization and

*I gratefully acknowledge funding support from the Jan Wallander and Tom Hedelius foundation (grant no W2015-0445:1) and Sweden's governmental agency for innovation systems, Vinnova (grant no 2014-06045). Parts of the empirical section were earlier presented in a working paper with Jonas Ljungberg "Innovation and economic growth in the Swedish engineering industry, 1914-2014", given at sessions at the European History of Economics Society Annual Conference in Pisa, 2015, the Swedish Economic History meeting, 2015, Umeå and at the Department of Economic History, Uppsala university. I wish to acknowledge, without implicating, seminar participants for useful suggestions and in addition Fredrik NG Andersson, Thor Berger and Jonas Ljungberg for discussions and criticism. The usual caveats apply.

automation technology as well as the development of renewable energy technology. Meanwhile, such broad technology transitions are not automatic: theory and historical evidence on technology shifts present compelling arguments that successful transitions are protracted processes that require investment, infrastructural and institutional innovation.

This study departs from the notion that understanding present challenges and recent developments in technology is contingent on our understanding of the long-run dynamics of technology shifts and the historical interaction between innovation and processes of economic growth. Historical work has argued this relationship to be wave-like (Freeman and Louça, 2001; Perez, 2002, 2010) or one where pervasive new technologies are diffused sluggishly before complementary innovation and investment has come into place (Brynjolfsson et al., 2018; Lipsey et al., 2005), producing S-shaped growth trajectories. In a similar perspective, the recent decline in growth, if not a statistical artefact (Mokyr, 2018), has been suggested to be understood as the growing pains of new technologies (Brynjolfsson et al., 2018; Mokyr, 2018). In important respects however, narratives about large-scale technological transitions, industrial renewal and growth have yet to be confronted with long-run systematic studies of innovation patterns and their relationship with long-run fluctuations in economic activity. Part of the issue is methodological: innovation is subject to problems of measurement and the choice of innovation indicator may matter in a non-negligible way (Kleinknecht et al., 2002).

The present paper makes a novel contribution to our understanding of long-run patterns of innovation by investigating innovation in the Swedish engineering industry during the years 1909-2016. Previous research on innovation output has borne out mixed results. This makes it possible to detail the major technology transitions and long-run trends and to compare innovation activity with variations in economic growth. Moreover, innovation output is compared with patent statistics in order to discuss how the choice of innovation indicator may influence our understanding of medium and long-run trends. In order to reliably expound the relationship between short, medium and long-run variations in innovation and economic activity wavelet analysis is used, allowing for phase shifts and structural breaks in periodicity (Percival and Walden, 2006). In order to explain the patterns observed, innovation biographies are used. The rest of the paper is organized as follows. Section 2 introduces a theoretical review that places the current study in relationship with previous literature. The data and methodologies used are presented in section 3. The results from the empirical analysis are presented in section 4, followed by a concluding section.

2 Trends and waves in innovation activity

What do we know about short and long-run patterns in innovation activity? A fundamental discussion on innovation concerns whether innovation is subject to decreasing or increasing returns to research in the long-run (Bloom et al., 2017; Strumsky et al., 2010), and in a more contentious version, whether radical innovation is petering out since the post-war era (e.g., Huebner, 2005). The view that technological change is a process of recombination of the set of available technologies is fundamental (Arthur, 2007; Arthur and Polak, 2006; Gilfillan, 1935; Schumpeter, 1939; Usher, 1954; Weitzman, 1998) and has generally be taken to imply that new technologies add to the set of possible combinations. In this perspective, the number of possible combinations grows exponentially, and eventual obstacles to innovation lie not so much in the exhaustion of new opportunities as in the (in)ability to process an abundance of opportunities into new innovations (Weitzman, 1998). Others have proposed that innovation is subject to the same long-term dynamics as living systems (Heylighen, 1999), in that owing to increasing complexity, there are decreasing returns to search (Strumsky et al., 2010). Similarly, the hypothesis of barrier-breakthrough (Ayres, 1989) stipulates that the rate of innovation slows down when a technology approaches its technological limit since R&D is most expensive, and returns to R&D smallest, near the technological limit. In the view of some authors, these views can both be correct, if the technological system time and again bootstraps itself towards more complex but higher quality technologies. In this way, while individual technologies will encounter decreasing returns to search, change in the composition of the technological system may imply a countered innovation to research ratio (cf. e.g., Mokyr, 2018: "science allows us to build taller and taller ladders to reach higher-hanging fruits"). This makes it necessary to understand innovation trends both in the very long-run and in a perspective which takes into account major shifts in the character of technological change. This is the first objective of this study.

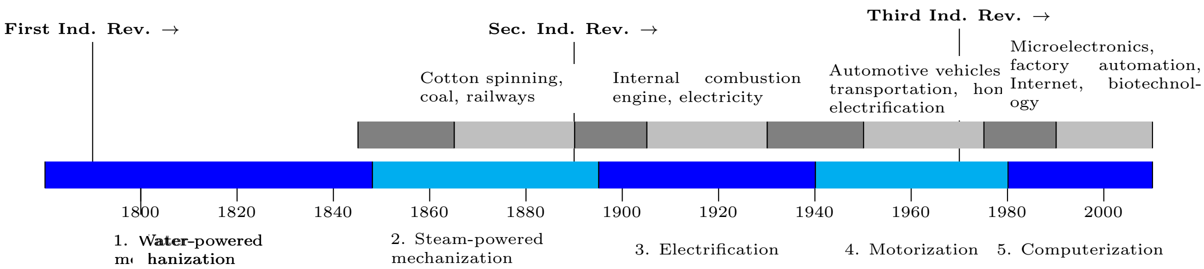
The second objective of this study is to examine the patterns in innovation activity and their relationship to shorter and longer variations in economic activity. To date, the most articulated theories of technology shifts posit that technology shifts are protracted processes in which major innovations give stimulus to complementary activities and innovations, which only gradually have enabled a more widespread use of the technology (Bresnahan and Trajtenberg, 1995; Freeman et al., 1982). Several analytical frameworks have been proposed along these lines to describe major technology shifts in modern history and their transformational impact on society. The notion of techno-economic paradigms (TEPs) (Perez, 1985) refers to the economic and technological factors that select and guide the direction of innovation and search activity. Successive technological revolutions are changes in techno-economic paradigms based on the diffusion of interconnected sets of radical innovations (Freeman and Louça, 2001; Perez, 2002) that through the interactions and complementarities between innovations, producers and users open up vast opportunities for the development of new technology, infrastructure and industrial activity.

Work in this tradition has emphasized the connection between such technological revolutions, changes in TEPs, and long waves of economic development (Freeman and Louça, 2001; Perez, 1983; Tylecote, 1992, 1994). Specifically, Freeman and Louça (2001) linked the technological revolutions to five Kondratiev waves of lengths of ca 50 years, shown in Figure 1 and detailed in Table A.1. In these technological revolutions, a dynamic tension has existed between industries, where leading branches or "motive branches" produce the "key inputs", such as cotton and pig iron in the first and coal in the second technological revolutions (Freeman and Perez, 1988; Perez, 1983). Carrier branches, like textiles or steam engines implement the "key input" and induce new investment opportunities in "induced branches" once necessary organizational and institutional innovations are in place. Towards the end of a long wave, infrastructures have been deployed based on the radical innovations, e.g., railroads, electricity, roads and the Internet. Hence, through the deployment of radical innovations, such as the steam engine, electric motor or microprocessor, forces of growth have been put in motion successively through dynamic interplay between industries, leading, eventually, to large productivity advances in the entire economy. It is fair to say however that such an intricate connection been broad technology shifts and Kondratiev waves has not been easy to demonstrate empirically, let alone the existence and periodization of Kondratiev waves. Therefore Perez (2002; 2010) later suggested the term "great surges of development" to set focus on the transformation of the socio-economic sphere rather than up- and downswings in economic activity, resulting in a slightly different periodization.

Based on historical national accounts, Schön (1994, 1998, 2010) has proposed a similar characterization of patterns in Swedish economic growth as fundamentally connected to investment patterns and the diffusion of major innovations in technological systems. This perspective is however based on different notions and suggests a different periodization. It adopts the economic historical perspective that we have seen three major technology shifts, called industrial revolutions, the first being the industrial revolution of the 18th century, based on the development of steam powered technologies. The second industrial revolution of the 1890s was based on the diffusion of technologies related to the internal combustion engine and electric motor, and the third on the diffusion of microelectronics and digital technologies. A central notion to theorize these deep transformations is "development blocks" (Dahmén, 1942, 1950), sets of complementary activities that are centered around innovations. Importantly, innovations respond to imbalances (compare Rosenberg, 1969) within the development blocks and the opportunities and complementarities brought forth are a major expansionary force for further development. Major development blocks have brought major societal transitions, energy transitions (see Kander et al., 2013), while other development blocks have been centered on smaller sets of synergistic innovating firms (Carlsson and Soete, 1991).

In the view suggested by Schön 1994; 1998; 1998, structural change has altered its focus between the *transformation* and renewal of economic activities and their *rationalization*. In Figure 1, Schön's periodization is given among with core development blocks (see also Table A.2). Following structural crises of the late 1840s, 1890s, 1930s and 1970s, new major development blocks have been formed around coal, steel and railways (mid-19th century), around electrification and the combustion engine (1890s and 1930s), and around micro-electronics and e.g., biotechnology from the 1970s and onwards. In this perspective, while the underlying inventions may have been developed earlier, structural crises have broken down obstacles to the implementation, diffusion and further development of such technologies (Schön, 1991, 1994, 1998). In this phase, long-term investments in industrial plants and knowledge have dominated, overcoming obstacles and enabling the wider exploitation of new technologies: a period of *transformation*. As a result of the long-term character of investment, the rate of investment has risen in comparison to output during transformation periods. The diffusion of

Figure 1: Technology shift chronologies. TEPs (Freeman and Louça, 2001), industrial revolutions and major development blocks in Sweden (Schön, 2010).



new technology has been concentrated to industrial applications and investment has been focused to home markets. Schön argued that such investment patterns have historically dominated during a period of 15-25 years. Periods of renewed technological development have been followed by "transformation crises" (in the 1910s, the Korea recession of the 1950s, and 1990s), which have been followed by reinvigorated growth in the new technologies.

The second phase of this historical periodization owes to stability and growing competition between firms, implying increasing focus on *rationalization* and efficiency, through lowering production costs or specialization. As the major development blocks mature, a wider diffusion of new technologies is made possible, reaching final consumers, as was arguably the case in the 1960s and 2000s. Culmination crises, e.g., the IT bubble of the 2000s, have marked the culmination of the transformation process and a shift of emphasis towards intensified competition and rationalization rather than continued transformation and innovation. The structural crises are, according to Schön, a manifestation of the weakened expansionary force of the mature development blocks.

It is important to note that the chronologies of investment and technology shifts are based on evidence about technology diffusion or investment rather than innovation processes per se. In other words, these frameworks have yet to be confronted with systematic long-term data on innovation output. Nevertheless, the historical literature provides several claims about when innovation activity has tended to occur. In a strand of literature, elaborating on original insights by Kondratiev (1935) and Schumpeter (1939), innovation has been posited to arrive in "clusters" or waves. Simplified, the literature contains three varieties of clustering hypotheses (see Silverberg, 2007; Silverberg and Verspagen, 2003 for a review):

1. Innovations cluster stochastically

2. Innovations cluster during economic downturns

3. Innovations cluster during economic recoveries

The first hypothesis, a minimalistic version of Schumpeter's (1939) argument, is that radical innovations are exogenous to economic mechanisms, but in themselves engender further innovation: "innovations do not remain isolated events, and are not evenly distributed in time, but [...] on the contrary they tend to cluster, to come about in bunches, simply because first some, and then most, firms follow in the wake of successful innovation" (Schumpeter, 1939, p. 100). This proposition may be called stochastic clustering, as it is not stipulated to have a relationship to economic mechanisms.

The second hypothesis can be traced to an earlier contribution by Kondratiev (1935) who had noted that the long waves of 45-60 years of duration he had observed in prices, foreign trade and production, also applied to technology: "during the recession of the long waves, an especially large number of important discoveries and inventions in the technique of production and communication are made, which, however, are usually applied on a large scale only at the beginning of the next long upswing" (Kondratiev, 1935, p. 111). The hypothesis of innovation-driven economic cycles was brought up by Gerhard Mensch (1979) who suggested a 'depression-trigger' mechanism of basic innovations. In empirical studies of basic innovations, he suggested that they were clustered in periods of depression (the 1820s and 1830s, the 1880s and the 1930s). This proposition has obtained support from some studies (Kleinknecht, 1981; Kleinknecht and van der Panne, 2006), but has since been a controversial claim (see e.g. Silverberg and Verspagen, 2003).

The third hypothesis suggests that the bunching of innovations takes place in the recovery of economic downturns. Clark et al. (1981) and Freeman et al. (1982) suggested that waves of innovations first of all "arises from the imitation and diffusion process and from the clustering of technically related families of innovations and inventions" (Clark et al., 1981, p. 321). They also suggested that innovations follow profit expectations, hence more likely to take place during the recovery from economic crises. Mensch was "looking at the wrong 'swarms'" (Freeman et al., 1982, pp. 66-67). Kleinknecht (1981) noted however, that the depression-trigger mechanism for basic innovations did not exclude subsequent waves of innovations to occur during a recovery.

In a Swedish context, Schön (1994) noted that there were cases when breakthrough innovations were made following the endeavors of the industry to rationalize production. Development blocks around railways and engineering in the 1850s were based on innovations developed some 30 years before. The second industrial revolution was based on important advances in the 1870s: the dynamo and electric lights were used in industry electrification and appeased rationalization in the 1890s. It was also in the 1890s that innovations of alternating current in a three-phase system solved the critical problem of transforming higher and lower voltage.[1] In the engineering industry, the introduction of electric motors on each process machine allowed the elimination of mechanical power transmissions and enabled large rationalizations and savings in the 1920s. This experience might have enabled innovations in electric motors in the 1930s. Similarly, some breakthrough

[1] The three-phase electric power system was independently pioneered, among other inventors, by Jonas Wenström.

Table 1: Description of key variables

Variable	Description
Commercialization year	Year of commercialization of the innovation.
Product type	The product code (ISIC Rev. 3) of the innovation (1970-2016).
Knowledge-base complexity	The number of knowledge bases required for the innovation (a knowledge base corresponds to a two-digit ISIC (Rev. 3) code).
Use of major technology	The innovation uses a major technology (electricity, combustion engine, ICT or renewable energy) in its core functions.
Eco-innovation	The innovation reduces the use of natural resources (including materials, energy, water and land) and/or decreases the release of harmful substances

innovations in ICTs, such as the integrated circuit (1961), were outcomes of the efforts to rationalize production in the 1960s. As of yet, these observations have not been substantiated with systematic support.

3 Methods and Data

3.1 Innovation data

Earlier research on longitudinal innovation patterns have for the most part used R&D and patents as proxies for innovation. These indicators are for well-known reasons however not necessarily closely related to innovation activity, although they may convey similar information in cross-sections (e.g., geographic data, see Acs et al., 2002). Conceptually, patents may be concerned with inventions, or 'normal science' rather than economically significant innovation, and not all innovations are patented. Similarly, R&D does not necessarily result in innovation, nor is it the only input that might matter for innovation. Important in the context of long-run studies is also that temporal variations in patenting are likely to deviate from the development and commercialization of innovation and that patents may be subject to long-run differences in patent laws, incentives and patenting strategies. In short, patent regimes vary over time and across industries and countries why comparative analyses must be careful (see, e.g., Lerner and Seru, 2017).

This study is primarily based on the collection of observations on actual innovations reported by trade and technical journals according to the so called Literature Based Innovation Output (LBIO) method (Kleinknecht and Reijnen, 1993). In addition, this study uses Swedish patent applications filed to the USPTO. This source is afflicted by long-run patent strategies and changes in patenting incentives, and would optimally be complemented by national patent statistics. While there are statistics from 1963 and Swedish patent office statistics have been collected for the late 19th century (Andersson, 2016a), no statistics of patents of Swedish origins are available at the aggregate level for the period studied.

The main innovation output indicator is based on a Swedish innovation database (SWINNO) applying the LBIO method to trade journals (Sjöö, 2014; Sjöö et al., 2014; Taalbi, 2014). This source material contains not only observations of when innovations were commercialized but also rich information about innovation biographies and innovation characteristics. While the LBIO method has been applied in different ways (see Kleinknecht et al., 1993), the SWINNO database includes observations only from edited sections of the trade journals. The edited articles are usually based on a selection made by journalists with some expertise in the field. In other words, advertisements and notification lists, based on press releases of firms, are not included.

The SWINNO database for the period 1970-2007 was based on 15 trade journals covering the Swedish manufacturing industry and ICT services. The database includes more than 4,000 innovations, commercialized by Swedish firms, whose characteristics and innovation biographies are described in detail. In order to study innovation patterns over a longer period of time, the data series of the present paper is based on two of these journals, *Teknisk tidskrift* (renamed *Ny Teknik* from 1967) and *Verkstäderna*, the first more general and the latter covering the engineering industry. These two journals reported together 53% of the total number of innovations during the period 1970-2016. This paper relies uniquely on these two journals for the whole period, 1909-2016. *Teknisk tidskrift*, started in 1871, was published by the Swedish Association of Technologists, and continued under the name *Ny Teknik* from 1967, published by the Swedish Association of Graduate Engineers. *Tidningen Verkstäderna* was founded in 1905 as the journal of the engineering industry's employer's association (Sveriges Verkstadsförening).

This database covers significant innovations in the engineering industry and ICT services, with the exception of specialized suppliers of machinery. To investigate the coverage, several tests have been carried out (see Sjöö et al. 2014 and Kander et al. 2018 for methodological discussions and details). In comparison with the few other studies on Swedish major innovations, we find a decent overlap. Out of 71 major innovations in engineering listed by Wallmark and McQueen (1991) for the period 1945-1979, 54 (76%) were included in either *Ny Teknik* or *Verkstäderna* (or both). Out of 49 engineering innovations listed in another similar publication (Sedig, 2002), 40 (81%) were included in the two journals. Those that were not covered were mostly special-purpose machinery (e.g., for the paper and pulp, publishing and printing or chemical industries), and others commercialized by foreign companies.

For the period since 1970, the editorial policies of the journals have been generally unchanged (Sjöö et al., 2014). For the entire period studied, the structure and content of *Verkstäderna* was also generally consistent. *Teknisk Tidskrift* however has had some changes in the structure and content. Before the 1970s, part of the journal consisted in longer articles written by invited specialists. While most of these articles had an innovation focus, some included articles gave an overview of a technological field, with innovations brought up in passing.

These two journals together collect 3,947 innovations in the period 1909-2016, most of which were developed in the last 40 years (Table 2). The average innovation count was 36.9, with a peak in the period 1970-1989 of 71.8 innovations on average (see empirical sections for further analysis).

Table 2: Summary of innovation counts

	Total	Period average
1909-1929	281	14
1930-1949	333	17.5
1950-1969	582	30.6
1970-1989	1365	71.8
1990-2016	1386	53.3
Total	3947	36.9

For each of these innovations, several variables have been collected. Those used in this work are summarized in Table 1. In the vast majority of cases the commercialization year of the innovation is based on explicit mentioning in the article. In cases where such a year was not possible to assign from journal information, the year of the journal article was used as a proxy. The commercialization is used to construct series of the sheer counts of innovations over time. A more sophisticated measure takes into account that the complexity of innovation processes may change over time. For instance, a new cell phone (ISIC 32) may also have required the development of software (ISIC 72) or telecommunication technology (ISIC 64). The knowledge base complexity measures the number of knowledge bases that were required to be developed for an innovation, during the subperiod 1920-1916. Knowledge bases are here defined through ISIC Rev. 3 two-digit industries.

In order to date major technology shifts, innovations were also classified if they incorporated a technology linked to major development blocks in their core functions: electricity, combustion engines, ICTs (microelectronics) and renewable energy technologies. In addition, we also study the broader category of "eco-innovation" being defined by the Eco-Innovation Observatory (2012, p. 8) as the "introduction of any new or significantly improved product (good or service), process, organizational change or marketing solution that reduces the use of natural resources (including materials, energy, water and land) and decreases the release of harmful substances across the whole life-cycle." Eco-innovations hence include fossil-fuel based innovations that aim to reduce the exhaust or harmful substances, as well as strictly speaking non-renewable technologies like nuclear power and fuel cells.

3.2 Wavelet analysis

In order to carry out a systematic investigation of long-run variations in innovation and economic activity and to compare those variations, we use a wavelet multiresolution analysis that decomposes a time series into components with different frequencies (Percival and Walden, 2006). Hence it is possible to compare short, medium and long-run variations in innovation with similar variations in patents and economic activity. Wavelet analysis has important advantages over spectral decomposition methods (like the Fourier transform) that assume a deterministic underlying processes localized only in frequency. Wavelets are localized in both time and frequency, which means that the underlying process can change over time.

In greater detail, a wavelet transform can be used to decompose a signal in the time domain into variations defined on a set of scales $j \in \{1, 2..., J\}$ with frequencies 2^{-j-1} to 2^{-j}. Let a time series $\mathbf{X}$ be represented as a column vector having the sequence $X_0, ..., X_{N-1}$ as elements. The discrete wavelet transform (DWT) is an orthonormal transform of $\mathbf{X}$, defined for any time series that has a dyadic length (i.e. $N = 2^J$). It is defined by the transformation $\mathbf{W} = \mathcal{W}\mathbf{X}$ with $\mathbf{W}$ a column vector of length N and $\mathcal{W}$ a $N \times N$ wavelet transform matrix defined through a particular type of wavelet filter (e.g., Haar or Daubechies). Orthonormality implies the important property $\mathcal{W}^T\mathcal{W} = I$, with I the identity matrix, from which it can be shown that the transform preserves the energy of the time series. The wavelet transform matrix is defined for a number $J+1$ of different scales and can be expressed in terms of $\mathcal{W} = \begin{pmatrix} \mathcal{W}_1 \\ \mathcal{W}_2 \\ \vdots \\ \mathcal{W}_J \\ \mathcal{V}_J \end{pmatrix}$, where the first elements are transform matrices of dimension $N/2^j \times N$ consisting of circularly shifted "wavelet filters" with elements h_{jl} corresponding to high frequencies. The last element $\mathcal{V}_J$ is a transform matrix of dimension $1 \times N$ consisting of circularly shifted scaling filter with elements g_{jl} that correspond to smooth variations (low frequencies).

In a similar way, the wavelet transform results in $\mathbf{W}$, consisting of wavelet coefficients $\mathbf{W}_j$ being column vectors of length $N/2^j$ and a scaling coefficient $\mathbf{V}_J$. These coefficients have been transformed from the time domain to the frequency domain. Using the orthonormality condition of the wavelet transform it is importantly possible to revert the transformation and recover a multiresolution analysis where the time series $\mathbf{X}$ is expressed as the sum of variations in given frequency bands 2^{-j-1} to 2^{-j}. This according to

$$\mathbf{X} = \sum_{j=1}^{J} D_j + S_J = \sum_{j}^{J} \mathcal{W}_j^T \mathbf{W}_j + \mathcal{V}_J^T \mathbf{V}_J \tag{1}$$

with D_j, called a detail, being the time series related to variations in $\mathbf{X}$ of frequency 2^{-j-1} to 2^{-j}, and S_J a smooth of frequencies 2^{-J} and below.

However, the DWT is sensitive with respect to starting year and the dyadic length requirement is restrictive. To overcome this, a maximum overlap discrete wavelet transform (MODWT) is defined in terms of circular shifts of the wavelet and scaling filters. In contrast to DWT, the MODWT is a non-orthogonal transform. The multiresolution analysis is given by

$$\mathbf{X} = \sum_{j=1}^{J} \tilde{D}_j + \tilde{S}_J = \sum_{j}^{J} \tilde{\mathcal{W}}_j^T \tilde{\mathbf{W}}_j + \tilde{\mathcal{V}}_J^T \tilde{\mathbf{V}}_J \tag{2}$$

where the tilde indicates the MODWT.[2]

[2] The wavelet and scaling coefficients for a level j are given respectively by applying wavelet filters $h_{j,l}$ and scaling filters $g_{j,l}$ of length L to the time series. Formally, $\tilde{W}_j = \sum_l^{L_j} \frac{h_{j,l}}{2^{j/2}} X_{t-l \mod N}$ and $\tilde{V}_j = \sum_l^{L_j} \frac{g_{j,l}}{2^{j/2}} X_{t-l \mod N}$, with $l \in \{0, \cdots, L_j - 1\}$ and $L_j = (2^j - 1)(L-1) + 1$. In matrix

MODWT permits a decomposition of the variance $||\mathbf{X}||^2$ of the time series in terms of the wavelet and scaling coefficients through:

$$||\mathbf{X}||^2 = \sum_{j}^{J} ||\tilde{\mathbf{W}}_j||^2 + ||\tilde{\mathbf{V}}||^2 \tag{3}$$

with $\tilde{\mathbf{W}}_j$ and $\tilde{\mathbf{V}}$ being the MODWT wavelet coefficients for scale j and scale coefficients respectively.

The wavelet decomposition and energy decomposition analysis is carried out in section 4.2 based on three key variables: the innovation count, USPTO patents and the industry investment ratio (Schön, 1998, 2010) defined as the industrial total gross fixed capital investment in fixed prices as share of manufacturing value added (fixed prices).

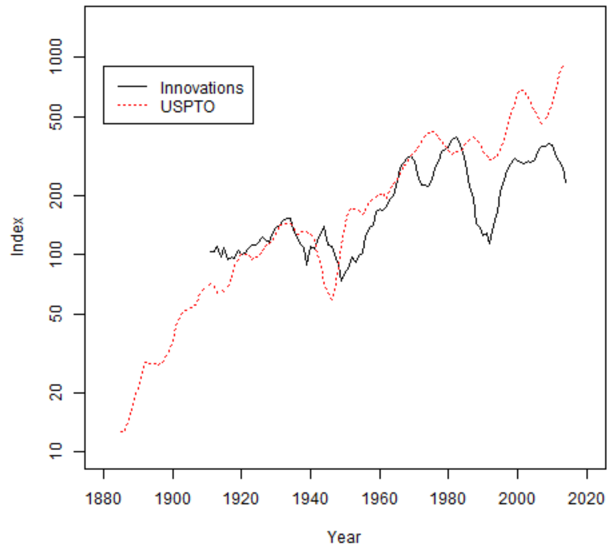
4 Results

4.1 Trends in innovation activity

The long-run trend in Swedish innovation activity is *prima facie* not straightforwardly determined from different innovation indicators. The crude counts of Swedish innovations and patents per capita (USPTO) reveal some differences in the long-run trends (Figure 2). USPTO patents have a slight stagnation from the 1970s, followed by an exuberant renewed increase from 1990s. Between 1920 and 2016 USPTO patents per capita increased almost 10 times. The Swedish innovation counts per capita fall in between, with a stagnant trend after the 1970s, having increased to more than 400% of the 1920 level.

notation, the rows of the wavelet transform $\tilde{\mathcal{W}}_j$ has as elements circularly shifted wavelet filters $\frac{h_{j,l}}{2^{j/2}}$, periodized to N, and analogously for $\mathcal{V}_j$.

Figure 2: Index of innovations per capita (1909-2016) and patents per capita (USPTO 1883-2014). Five-year moving averages (1920 = 100).

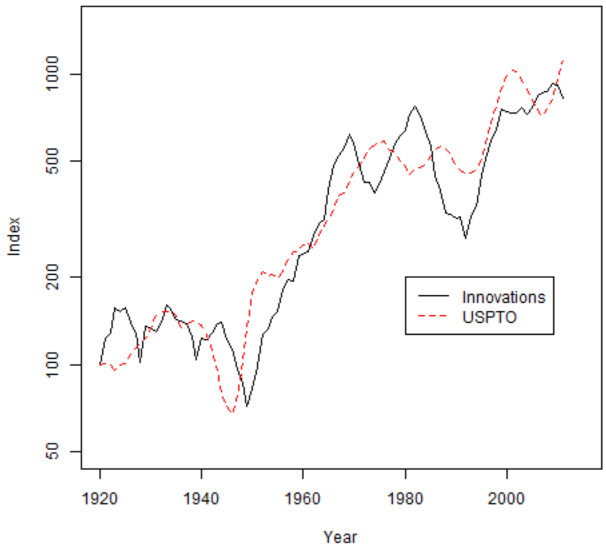


The differences can certainly to some extent be explained by changes in patenting behavior, as well as changes in patent laws and policies (e.g., Criscuolo, 2006). OECD (2011) has also suggested that patent quality has dropped drastically in major economies during the 1990s and 2000s. An explanation of the difference between innovation counts and patents is however, apart from the general notion that "not all patents are innovations", that innovation processes are affected by increasing complexity in many ways, which may not be taken into account in the sheer innovation counts.

With increasing complexity in the long-run, innovation may involve a significantly larger number of parts or require the integration of ever more diverse knowledge. There is a drawback of focusing solely on product innovations, since many process innovations and developmental advances may be contained in a single product, something which may conceal innovations contained in the production process. It is in other words possible for this reason that the decoupling of innovation counts and (USPTO) patenting in the long run is merely ostensible. By using the number of knowledge bases (ISIC) combined into an innovation, it is however possible to adjust the innovation counts to take into account possible changes in how innovation takes place and the possibility of an increased presence of vertically integrated innovation processes. Specifically, to measure knowledge complexity, we count the number of knowledge bases for which the innovation required improvement, as detailed in the previous section.

Our results (Figure 3) suggest that the knowledge complexity of Swedish innovations roughly doubled between the 1920s and 2013. This is consistent with Akcigit et al. (2013), reporting a similar figure for US domestic patents by using the average number of patent citations. When using these adjustments, patents and innovations behave similarly over time. This gives some indication that some of the long-run increase in patents is due to increasing product complexity, although

Figure 3: Knowledge base weighted innovations (log scale). Five-year moving averages (1920 = 100)



some of the later increase might be attributed to quality decreases in patenting.

The economic significance of these results is not obvious, since it is not settled whether the increasing complexity stems from a shift to more complex product types or increased complexity *within* product groups. In Appendix B, some indications are given through a shift share analysis for the period 1970-2016, decomposing the change in average knowledge complexity of innovations into changes within product groups or changes between product groups. The results suggest that most of the increase in complexity stems from increasing complexity within product groups, while about 20% of the change in average complexity is explained by bootstrapping towards more complex products.

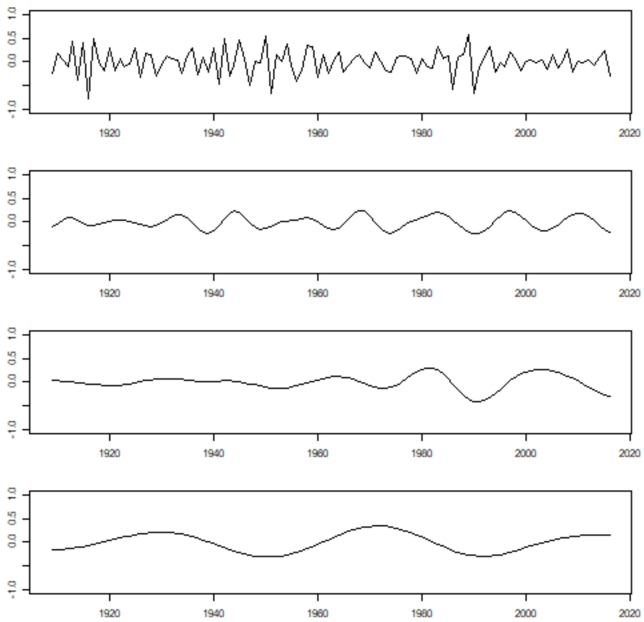
4.2 Innovation, investment and industrial revolutions

In order to compare the patterns of innovation with economic variations of different frequencies we use a wavelet analysis. Wavelet analysis does not require time series to be detrended or stationary, nor imposing deterministic cycles, which makes it a suitable choice for our purposes. Innovation and economic time series are decomposed through a wavelet transform, introduced in section 3. The present analysis employs the maximum overlap discrete wavelet transform (MODWT) using the Daubechies wavelet basis function. In our case, we decompose the logarithm of our time series x_t into five details D_{jt} and a smooth S_t trend: $x_t = D_{1t} + D_{2t} + ... + D_{5t} + S_t$ with $j \in \{1, 2, ...5\}$. All wavelet details presented are in log form, which means that they are the log of percentage deviations from the smooth. The first detail is a cycle of length 2-4, the second 4-8, etc. Of special interest are the long-run components, 16-32 and 32-64 year variations, since they may or may not be connected to structural cycles or Kondratiev waves (Andersson,

Table 3: Energy decomposition of innovations, patents and investment below/above trend line

	Innovations	Investment	Patents
D1 (2-4 years)	0.16	0.06	0.03
D2 (4-8 years)	0.10	0.14	0.03
D3 (8-16 years)	0.21	0.24	0.32
D4 (16-32 years)	0.31	0.18	0.28
D5 (32-64 years)	0.23	0.38	0.34

Figure 4: Wavelet decomposed innovation counts (2-8, 8-16, 16-32 and 32-64 year waves



2016b).

A basic analysis of variance (see eq. 3) is important to understand to what extent different cycles in the series contribute to the overall variations. The energy decomposition of innovation, investment and patents is given in Table 3. Since all series are non-stationary growth series we focus on the variations above/below the smooths and express the variance as percentage of the variance of de-trended series.

All of the series have significant variations at time horizons over 16 years. More than half (55%) of the variations in innovation output and 64% of variations in investment have length 16 to 64 years. The wavelet decomposition of innovations presented in Figures **??**-4 highlights that innovation activity was seeing high levels of new products in the 1930s, the 1970s and the 2010s. This corresponds to structural crises in Schön's 1994; 2010 crisis typology and roughly to long wave downturns. The magnitude of the long-run wavelets, 16-32 and 32-64 variations, has varied somewhat, but the cumulated number of innovations during the upturns have been roughly around 20% of the total count of innovations. The upturn during the 1920s and 1930s accounted for 48 innovations (18% of all launched),

Figure 5: 8-64 year waves in innovations and investment ratio

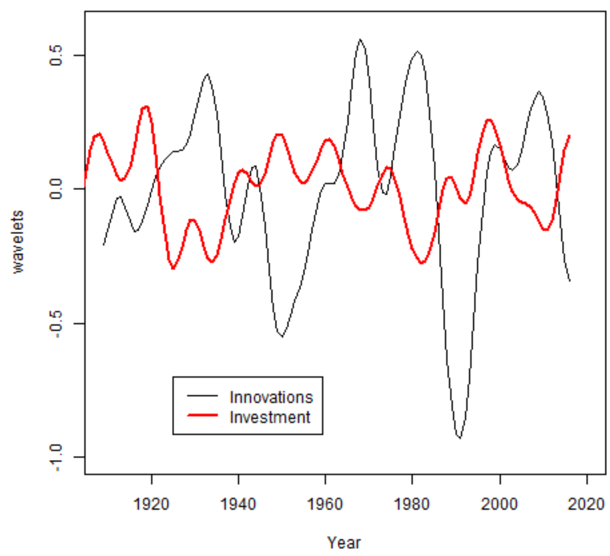


Figure 6: 32-64 year waves in patents, innovations and investment ratio

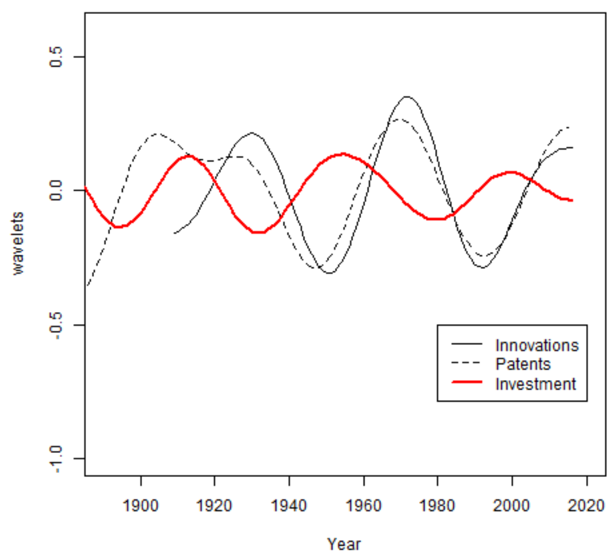


Figure 7: Scale-by-scale correlations between innovations at time t and investment ratio at time $t + x$ (95% confidence intervals).

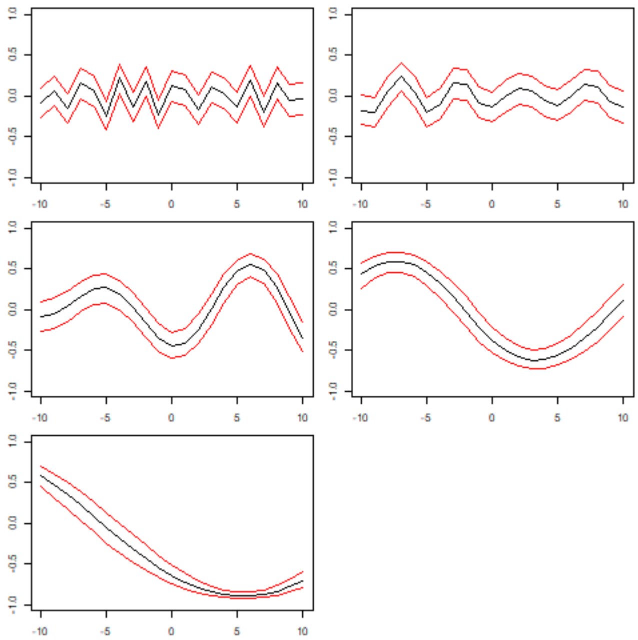
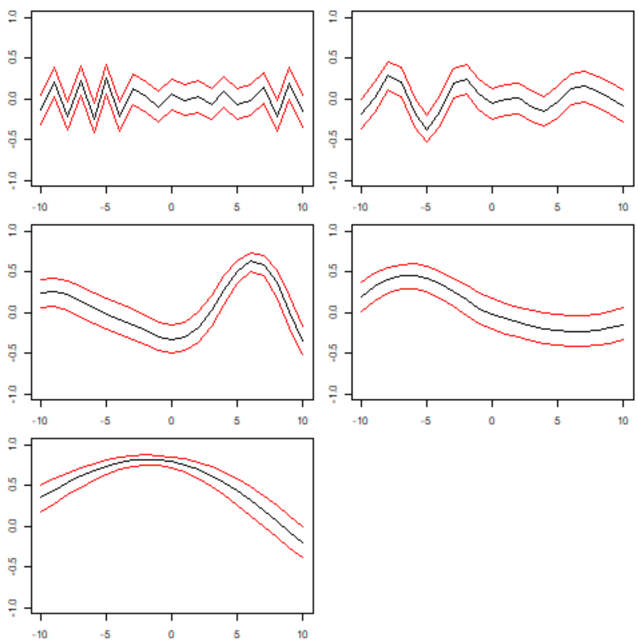


Figure 8: Scale-by-scale correlations between innovations at time t and USPTO patents at time $t + x$ (95% confidence intervals).



while the wavelet upturn in the 1960s and 1970s accounted for 273 (22%) and the upturn in the 2000s accounted for 154 innovations (18%).

Comparing wavelets between innovations, patents and investment, reveal further results of significance. First of all, we find support of a close, negative, connection between long-run movements in innovation and investment activity, in particular in the frequency bands 16-32 and 32-64 years. As shown in Figures 5 and 6, the innovation waves have occurred during downturns in the investment ratios and have been followed by increasing investment ratios, e.g., in the 1950s and the 1990s. More formally, wavelet cross-correlations innovation and investment are negative and significant at the 8-16, 16-32 and 32 to 64 year cycle lengths. Figure 7 suggests that innovations lead investment with a few years. We can also observe that innovations and patents have similar medium-run patterns and are highly correlated at the 1/32 to 1/64 frequencies. Figure 8 suggests that patents lead with some 5 years at the 32 to 64 cycles. This may suggest that patents and innovations capture similar long-run cycles, and that innovation tends to follow increased patent activity. There is however no significant relationship between these measures for variations below 16 years.

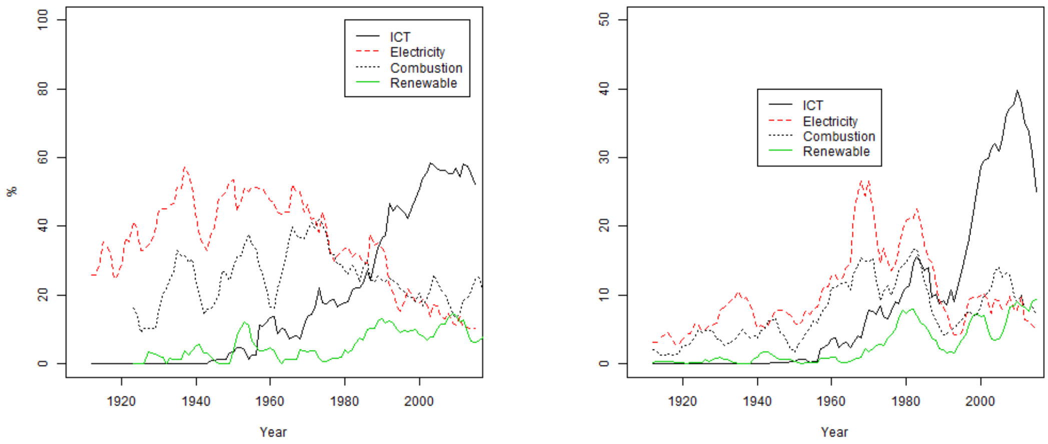
4.3 Successive technological revolutions

The patterns of innovation discussed in the previous sections are strikingly concentrated to the crisis periods of the 1930s, 1970s and 2010s. The mechanisms behind these patterns can be further analyzed through a qualitative description based on the collected innovation biographies. First of all it is possible to situate innovation activity in relation to the pervasive technologies underlying the broad societal and economic transformations of the 20th and 21st centuries. Figures 9a-9b show the share and count of innovations based on four major technologies: electricity, combustion engines, ICTs and renewable energy technologies. Before the 1970s most innovations were developed based on the GPTs of the second industrial revolution: electricity or combustion engines. In the 1920s, a burgeoning electrification had reached industries and several innovations were related to the electrification of locomotives and railways. The Swedish engineering company ASEA in particular made several innovations in diverse field pertaining to electrification. The first larger railway electrification was carried out by ASEA in 1915 in the ore transport railway between Kiruna and Riksgränsen. In the same year, the nearby Porjus electric power plant was inaugurated. Several firms developed locomotives and appliances during the coming decade, with ASEA as a central player. ASEA, among with AB Lindholmen-Motala and Nohab (Nydqvist-Holm AB), also developed new electric locomotives in the course of the 1920s.

Attempts at electrification were however so far confined to local industry and transportation, apart from the local home supply. The major problem for the establishment of a national electricity grid faced at this time stemmed from the long-distance transmission of electricity. This problem was solved in the 1930s with High Voltage Direct Current (HVDC) transmission systems, developed by ASEA engineer Uno Lamm, involving several components that solved critical problems. An important innovation was e.g., the ion valve, designed to solve the problem with arcs, which tend to occur more often in high voltage electric current (*Teknisk*

Figure 9: Innovations based on major technologies

(a) Shares in total (b) Absolute counts



tidskrift 1946, pp. 969-975; 1947, pp. 307-314; 1952, pp. 620-622; 1954, pp. 301-306). On the basis of the innovations made in the 1930s, ASEA developed the HVDC technology further in the post-war era, bringing it into commercial production in March 1954 as the transmission between Sweden's mainland and Swedish largest island, Gotland, in the Baltic Sea began (Fridlund, 1997).

The broader electrification that followed in the post-war era was profound. Roughly half of all innovations developed were now exploiting electric motors or electricity in their core functions (see Figure 9a). Many Swedish firms developed electric appliances and measuring instruments for industry and domestic use, with an exuberant expansion in the 1960s. One Swedish firm, AGA (Aktiebolaget Gasaccumulator) stood for a large number of such innovations, having developed the seminal AGA stove in 1929, the Geodimeter in 1959 and Thermovision (an infrared camera launched 1967), as well as an apparatus (AGA Sedator) that provided pain relief during deliveries using nitrous oxide, a heart-lung machine and other medical equipment. During this time, firms like Electrolux and Huskvarna occupied a dominant role in the field of home appliances, launching several new vacuum cleaners, stoves and washing machines in the 1950s and 1960s. As opposed to the expansion of the 1960s, the 1970s meant market saturation and a structural crisis, that spurred many firms to reorient their activities, some towards the burgeoning field of ICTs. Notably, Sweden's first personal compute, "ABC 80", was developed as a response to the crisis in home electronics (TV and audio systems).

Swedish innovations related to the use of combustion engines were most notable at first in the shipbuilding industry where diesel engines were introduced from the late 1900s and 1910s with Atlas Diesel being a notable supplier (launching its first marine diesel engine in 1907). Diesel engines were used as propulsion engine in new tank vessels and ships, and in practice, many motor constructors established a niche as suppliers to shipbuilders in waiting for an automotive boom. A notable innovation for the domestic automotive industry was the Hesselman motor launched in 1925, a hybrid between a diesel and Otto-engine, used primarily in heavier trucks. While the 1930s were more heavily oriented towards electric motors and systems, the Second World War meant a push for domestic development of transport equipment industries, such as aircraft and automotive vehicles. While imports of military airplanes were made in the beginning of the war, the Swedish government was eventually forced to call for domestic production. This was a significant boost to the formation of the Swedish airplane industry. SAAB, formed in 1937, having acquired its main competitor ASJA in 1939, started licensed production of airplanes and gained experience to develop its own airplanes, in part continuing experimental development projects of ASJA.[3] Likewise, AB Flygindustri had licensed production of airplanes, but could develop its first own airplane ”Fi 1” during the war (*Teknisk tidskrift* 1944, pp. 961-964).

Before WWII, producers such as Volvo and Scania-Vabis were focused on large trucks and buses. It was during and shortly after the war that Volvo and SAAB developed the first smaller passenger cars, sold in large numbers to the public. Volvo's manufacturing of cars had begun with the launch in 1927 of ”Volvo ÖV 4”, but it's first broadly successful car, ”PV 444”, was constructed during the war and sold in large numbers from 1947 (*Teknisk tidskrift* 1944, pp. 1085-1091). SAAB's development of automotive vehicles and motors drew from the experience made from airplane production during the war. The first SAAB car ”SAAB 92” was launched in 1949 with several novel constructions (*Teknisk tidskrift* 1947, pp. 539-540; 1949, pp. 197-202; Verkstäderna 1956, pp. 48-53). In the postwar era, the Swedish passenger car industry grew quickly. New cars made by SAAB and Volvo (e.g., ”Saab 93” and ”Amazon”, respectively, both launched in 1956) contained innovations made not only by the car producers. With a network of suppliers of engines and transmissions and other car parts, the Swedish automotive industry formed a development block (Elsässer, 1995; Schön, 2010) in which innovations, such as the three-point security belt (invented by Nils Bohlin in 1958), were successively integrated into new car models.

From the beginning of the 1950s both firms and research institutes became engaged in the development of automated calculators and computers, being early examples of the ensuing wave of industrial automation. The first Swedish computers were developed by state-owned Swedish Board for Computing Machinery (Matematiknämnden) in the early 1950s: BARK (Binary Arithmetic Relay Calculator), and BESK (Binary Electronic Sequence Calculator) (*Teknisk tidskrift* 1950, pp. 193-194; 1953, p. 1007; 1955, pp. 273-281; 281-292). Although the research activities of the Swedish Board for Computing Machinery were discontinued, the experience from the computers was the basis of further innovation in the field. In particular, the firms Facit (Åtvidaberg Industrier AB), SAAB, L M Ericsson, Standard Radio & Telefon AB and AB Addo advanced to the technological frontier during the 1950s and 1960s. Facit and SAAB developed their own versions of BESK under the names ”Facit EDB” and ”SARA” respectively. At this time, an technological imbalance emerged as data processing power increased and there were increased requirements for memory space, known as ”the tyranny of numbers”,

[3]Among the independently developed airplanes were ”B 18” (launched 1943), ”Saab 21 A” (launched 1945) and ”SAAB 91 Safir” (launched after the war).

acting as an obstacle to further improvement of transistor-based systems. This led some Swedish firms to develop new products, e.g., magnetic tape memory. More importantly, these imbalances drove the invention of the integrated circuit in 1961, by Robert Noyce at Fairchild and Jack Kilby of Texas Instruments, working independently. Such early advances enabled a vigorous factory automation during the 1960s. In the late 1960s, many firms in the machine-tool industry were integrating numeric control equipment into new machine tool innovations. By the 1970s, microelectronics innovations accounted for between 15%-20%, increasing steadily until the 2000s to 60%. This while innovations based on combustion engines or electricity have decreased drastically. The breakthrough embodied in Intel's 1971 microprocessor meant the emergence of exceptionally strong incentives towards product innovation. The diffusion of microprocessor based technology enabled new generations of machinery and instruments for control and measurement with vastly improved performance. At the core of this development was the development of control systems and computer equipment. Numeric Control (NC) systems had already been introduced into machinery during the course of the 1960s.[4] Swedish firms also were at the forefront of the development of robots.[5] During this period a wave of entrant firms emerged, aiming to exploit the new opportunities (for description and examples, see Taalbi, 2018). Other firms, facing negative performance, were able to diversify towards growing markets in electronics, notably Luxor Industries AB that responded by developing the Sweden's first personal computer ABC 80.

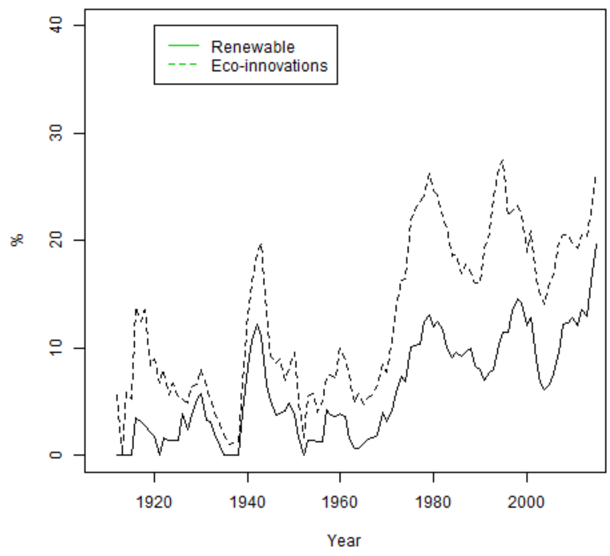
ICT innovations since the 1990s were by and large driven by the monumental opportunities brought about by the expansion of telecommunications and Internet. Major breakthroughs were made in the 1980s in several fields. Mobile telephone networks were pioneered in Sweden with NMT (Nordic Mobile Telephone system), invented by Östen Mäkitalo and launched in 1981. The first Swedish network was connected to the Internet in 1984. However, institutional barriers were present. Televerket's monopoly acted as such a barrier, since it impeded start-ups from entering into telecommunications. After the abolishment of this monopoly in 1993 and the public introduction of Internet in 1994, a large number of new firms entered into the market of telecommunication and digital technologies.

While these major opportunities were a basic facet of the IT boom, new firms were also often responding explicitly to critical problems that appeared in the deployment of Internet and telecommunication infrastructures. Innovations in both transmission systems and components for data and telecommunications were often the direct responses to obstacles to the introduction of e.g., broadband access technologies such as DSL, ATM or VoIP (Voice-over-IP). The continued expansion of ICT technologies has been driven by a vigorous number of entrant firms developing very diverse products in software, telecommunication services like Spotify, as well as medical and electronic equipment. In the wings of this

[4] Asea was one of the pioneers of the development of commercially available Computer Numeric Control systems (CNC) with its introduction of Nucon 1972 and Nucon 400 in 1977 (Ny Teknik 1972:3, p. 4; Verkstäderna 1977:4, p. 90).

[5] ASEA Robotics (ABB Robotics after 1988) was a market leader in this field, launching several notable robot innovations during the period studied. ASEA's IRB 6 launched in 1973, was the first wholly electrical micro-processor controlled robot commercially available.

Figure 10: Share of renewable energy and eco-innovations (five-year moving averages)



expansion, one also finds numerous innovations towards the end of the period, exploiting 3D-printing techniques and robot and software-based technologies aimed for industry automation, which allegedly and quite possibly, is carrying the next wave of industrial renewal.

To understand the development of environmental innovations it is instructive to study both eco-innovations and the sub-category of innovations related to renewable energy technologies (Figure 10. These innovations have until the 1960s had an occasional presence. Eco-innovations have been particularly pronounced during WWII, owing to a raw material shortage, the oil crises of the 1970s, and more generally from the 1990s and onwards. Excepting innovations in hydropower, renewable energy innovations have similarly been clearly connected to pressing circumstances and energy crises. The First World War meant drastically increasing prices for coal and oil, which spurred a few coal and oil saving technologies, and reinvigorated interest in using peat, e.g., for powering locomotives. Similarly, the Second World War brought with it import restrictions, particularly felt in the shortage of gasoline and fossil fuels, being very rare in Swedish soil. After Sweden was cut off its import of petrol from the North and South Americas in Spring 1940, the response was swift. These difficulties prompted search for alternative fuels and vehicles or generators making possible the use of other power sources, mainly based on firewood. A handful of innovations and new constructions were hence developed aimed to enable the use of generator gas for vehicles. Electric vehicles also made a brief but ultimately unsuccessful comeback in a few innovations. For example, an electric truck (EBV 12-2), developed by the electric car company (SEA), was used during the war, but could not compete with its gasoline driven relatives once the war was over (*Teknisk tidskrift* 1940, pp. 389-393; 1966, pp. 439-446).

The energy crisis of the 1970s meant a strong push for the search of alternative energy technologies, as has been evidenced in other work (Taalbi, 2017*a*,*b*). Not only was there an economically induced need to replace oil dependency, but a series of political and institutional measures had been taken with the Environmental Law of 1969 and e.g., Sweden's first government bill considering energy policy issued in 1975, containing an alternative fuel strategy. A broad set of innovations and technologies were now developed. Attempts to replace oil were initially directed towards other fossil fuels for energy production, such as district heating and heating pumps Kaijser1988, and methanol for engines (Sandén and Jonasson, 2005). Owing to the rich wood and forest resources, forest residue was an obvious alternative fuel. Owing to a wood shortage as well as the energy crisis, many innovations were developed to achieve profitability in the processing of forest residue. A few innovations were also developed to enable the use of peat as a fuel source. A more successful path however, was to use gasified biomass, a field in which Swedish firms have been internationally prominent (Johnson and Jacobsson, 2001). Although the Scandinavian climate does not provide a comparative advantage in solar energy technology, several innovations were developed in the 1970s and 1980s to enable seasonal and long term storage of summer excess energy, also being tested in large-scale housing complexes. As the price of solar energy cells has been diminished and most technical obstacles solved, several innovations based on solar cells emerged in the last ten years of the period studied. Following the oil-crisis, wind power technologies began to be explored on a global scale. In Sweden, a wind energy programme was supported until the mid-1980s. For instance, government funding was granted in 1975 for Saab-Scania to develop Sweden's first wind turbine (Bergek and Jacobsson, 2002; *Ny Teknik* 1976:41, p. 22). However, lack of legitimacy and political decisions led to reduced ambition in the mid-1980s (Bergek and Jacobsson, 2002). Since then several Swedish firms have developed components for wind power stations, e.g., ball bearings for wind power turbines (by SKF) and wind power generators (ABB).

After the production of electric cars had been cancelled in the late 1940s, interest in electric cars did not re-emerge until the late 1960s as a result of the increasing awareness of environmental issues and the energy crisis. Costumer-demand, environmental awareness and sharpened legislation has since then also driven technological development in this direction (Elsässer, 1995), in several Swedish innovations including early electric cars (e.g., the electric car "Tjorven" used in Swedish postal services) and more recent development of hybrid cars, batteries (e.g., by ABB in 1988), electric motors and innovative solutions for charging stations in the last ten years. A modest surge in the 2010s (Figures 9a-9b) in renewable energy technologies is attributable to the maturity of several of the technologies, including electric cars and solar energy, as well as the rational use of digital technologies to attain reduced energy consumption.

5 Concluding discussion

This study has examined patterns of innovations in relation to economic activity using entirely new evidence for Sweden. The results presented do not unanimously support a view of either technological stagnation or exponential innovation rates as suggested by recombinant growth perspectives. The long-run trend of innovations per capita is clearly positive, but exceptional rates of innovation were reached in the 1960s and 1970s. This could be interpreted as a "peak innovation" in the past. Care must however be taken in interpreting long-run innovation counts since importantly, innovation processes have become more complex, integrating more functions and components into system innovations that were previously marketed in modules. Indeed, accounting for increasing complexity, innovations, as well as patents, increase both in absolute terms and relative to population.

In this context, one should note that the current study has two main limitations that raise further questions and point to further empirical work. In particular, the hypothesis that innovation is bootstrapped towards more complex products requires a more thorough treatment by considering innovation in other parts of the manufacturing and service sectors. Moreover, a more thorough investigation of long-run patterns in innovations with different degrees of novelty would be in place owing to the different hypotheses attached to radical innovations, and the possibility of secular changes in the impact of innovation on growth. It is also to be noted that systematic comparisons of long-run patents and innovation output with input measures (R&D) is left for future research.

The second issue studied in the present work is whether innovation clusters in time and how innovation activity relates to economic activity. In this regard, this study has been a first attempt to confront historical narratives with trends in innovation activity. In many respects, the results support an interpretation of industrial transformation suggested in previous works on Swedish industrial transformation (Schön, 1991, 2010), in which the long-run dynamics of innovation activity is intimately linked to the evolution of major development blocks based on electricity, combustion engines and ICTs. In fact, the results point to a stronger connection between innovation and economic transformation than theoretically stipulated. Specifically, rates of innovation have been culminating historically in periods of intense industry rationalization and structural crises, thus forming the basis of renewed investment expansions, specifically in the 1930s, the 1970s, and the 2010s, all "downswing phases". A closer look at the mechanisms responsible for innovation activity suggests several mechanisms that can explain the clustering of innovations in these decades. Schön's suggestion that innovation has resulted from the attempts of industry to rationalize production gives a historically important mechanism for the emergence of breakthrough innovations in electrification during the 1930s and in ICTs during the factory automation of the 1960s and 1970s. The emphasis in later years on the application of digital technologies in industry automation has likewise brougth forth advances in 3D printers and automation technology. However, other factors have also mattered, in particular during structural crises when negative performance has played a role (see also(Taalbi, 2017*b*)). For instance, the first Swedish personal computer resulted from an attempt to diversify from shrinking television and radio apparatus markets. Moreover, breakthroughs in renewable energy technology have been tightly connected with energy crises, as well as environmental and energy policy measures, in particular during the 1940s and 1970s.

The results of this study have corollaries for both research and policy. First of all, the results point to the difficulty of measuring long-run trends in innovation activity. In particular, the increasing complexity in the knowledge bases that are recombined into innovations (or patents) constitutes an important structural change in the way that innovation takes place. While the tendency towards greater complexity is well-studied in the patent literature, long-run analysis of patents tends to see view knowledge complexity as a input factor. The suggestion made here is however that complexity is an output factor that should be taken into account in constructing innovation (or patent) counts, since it in our case reflects the vertical integration of many products. The use of innovation output indicators must hence be complemented with information about (knowledge-base) complexity in order to provide a sensible basis for inference about long-run trends.

Our results also give empirical clues to inform our understanding of long-run socio-technical transitions (Geels, 2005, 2007). The finding that major innovations were made during periods of intense rationalization in traditional industries should be viewed as an empirical support for the notion that niche spaces have been instrumental for radical innovation (Geels, 2005; Schot and Geels, 2008). Breakthrough innovations like the integrated circuit, or similar Swedish innovations in the burgeoning ICT industry, were for instance developed in the wings of industry automation. Importantly, our historical analysis also leaves considerable room for agency responding to micro, regime or system-level imbalances by way of innovation, viz. a creative response, especially during the downturn phases. As it were, major crises can be strong signals for industrial transformation and windows of opportunity, especially if important breakthroughs have been made before. The creative response to perceived and actual obstacles and imbalances is arguably a neglected feature in the literature of socio-technical transitions. The perhaps most obvious example is during the 1970s when most innovations were responses to a set of economic, social and environmental, imbalances of the traditional Fordist and oil-based industries (see also Taalbi, 2017*b*). In particular, since the 1970s eco-innovations were explicitly responding to structural imbalances that had emerged in the traditional fossil fuel-based industries.

The results are also consistent with the view that the innovation waves and the wider diffusion of innovations are enabled through complementary investment and innovations that break down barriers. The close connection between innovation waves and subsequent investment and diffusion could be taken to suggest that agents in the economic or political spheres have historically been able to create conditions for further diffusion and innovations and implementation of technology shifts. However, this ability has not been invariant. Sustainable energy technologies are a case in point. The surge in innovations during the 1970s was certainly aided by new environmental legislation, energy policies and public investment programmes. However, they have so far struggled with technological as well institutional obstacles to their diffusion. This places (as stressed in e.g., Freeman and Louça, 2001; Freeman and Perez, 1988; Schön, 1991, 2010) an important role for policy in fostering synergies between emerging technologies in order to resolve obstacles, something which typically requires significant institutional and political innovation.

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Appendices

A Supplementary tables

Table A.1: Technological revolutions and Kondratiev waves.

Technological revolutions	Major innovation(s)	Leading branches
1. Water-powered mechanization of industry	Arkwright's Cromford mill (1771)	Cotton spinning, Iron products
2. Steam-powered mechanization of industry and transport	Liverpool - Manchester railway (1831)	Railways and railway equipment, steam engines, machine tools
3. Electrification of industry, transport, and the home	Carnegie's Bessemer steel rail plant (1875),	Electrical equipment, heavy engineering, steel products
4. Motorization of transport, civil economy and war	Ford's Highland Park assembly line (1913)	Automobiles, trucks, diesel engines, refineries
5. Computerization of entire economy	Intel microprocessor (1971)	Computers, software, telecommunications, biotechnology

Note: Based on Tylecote (1992), Perez (2002) and Freeman and Louça (2001).

Table A.2: Development blocks and structural cycles in Sweden.

Development blocks	Structural crisis	Transformation crisis	Culmination crisis
Steam engine, railways	1845/1850	1865/1870	1875/1880
Dynamo, electric motor, electricity	1890/1895	1905/1910	1915/1920
Combustion engine, automotive vehicles	1930/1935	1950/1955	1960/1965
Micro-electronics, biotechnology	1975/1980	1990/1995	2000/2005

Note: Based on Schön (1994, 2010).

Table A.3: Decomposed change in average complexity (logarithms), sub-periods and total

	$D_{between}$	D_{within}	D_{act}	D_{tot}
1970-1979 to 1980-1989	0.02	0.08	-0.01	0.09
1980-1989 to 1990-1999	0.01	0.08	0.01	0.1
1990-1999 to 2000-2013	0.03	0.13	-0.02	0.14
Total	0.06	0.29	-0.02	0.33

B Shift share analysis

Using a shift share analysis we decompose the complexity index for the subperiod 1970-2013 into a between effect (also called structural effect) and a within effect using a logarithmic mean divisia index (LMDI) (Ang, 2005). Letting c_t be the average number of knowledge bases in a period, we can define the change over the period as $D = c_T/c_0$, with $t = T$ and $t = 0$ being two separate periods. Letting I_t, S_{it} and c_{it} be the number of innovations at time t, share of innovations in industry i and time t and the average complexity in industry i and time t, it is possible to derive a decomposition of the change in average complexity D into an "activity effect", changes in complexity within industries, and structural changes between industries:

$$D = D_{act} \times D_{within} \times D_{between} \tag{A.1}$$

where D is the change in average complexity between two benchmark years. Specifically, the decomposed elements are

$$D_{act} = \exp\left((\sum_i \omega_i - 1) \ln \frac{I_T}{I_0} \right) \tag{A.2}$$

$$D_{between} = \exp\left(\sum_i \omega_i \ln \frac{S_{iT}}{S_{i0}} \right) \tag{A.3}$$

$$D_{within} = \exp\left(\sum_i \omega_i \ln \frac{c_{iT}}{c_{i0}} \right) \tag{A.4}$$

with $\omega_i = \frac{(C_{iT} - C_{i0})/(\ln C_{iT} - \ln C_{i0})}{(C_T - C_0)/(\ln C_T - \ln C_0)}$.

Our results for the period 1970-2013 (Table A.3) suggest that most of the increase in knowledge base complexity comes from the increasing complexity within industries, although a smaller effect also arises from structural change towards more complex products, in particular ICTs like electronic equipment, telecommunication and computers. These results are consistent with a tendency to bootstrap towards more complex products within and between industries.