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What drives innovation? Evidence from economic history[☆]

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ABSTRACT

An unresolved issue in innovation studies is to what extent and how innovation is affected by changes in the economic environment of firms. This study elaborates on a theoretical framework that unites theories of innovation as creative response and the economics of complexity. In the empirical section, results from a new micro-based database on Swedish product innovations, 1970–2007, are introduced. Applying the theoretical framework, both quantitative evidence and collected innovation biographies inform of the historical impulses that have shaped innovation activity in the Swedish economy in two broad surges during the 1970s and 1990s. The study shows that, rather than being the result of continuous efforts, most innovations were developed as a response to discrete events, history-specific problems and new technological opportunities. It is also suggested that patterns of creative response are industry-specific and associated with the radicalness and complexity of innovation processes.

1. Introduction

There is today a sizeable body of literature on the determinants of innovation activity. While a wide range of economic, social and technological incentives have been suggested as driving forces of innovation, there is hardly a consensus on how and to what extent innovation activity is the response to changes in the social or economic environment. In fact, modern research may be read to convey the message that a plethora of factors may matter and that there are large differences on a case to case basis, so that a universal theory of innovation appears unrealistic. Yet, it is hard to find comfort in such an outlook, perhaps because the perspective one takes on the driving forces of innovation carries large stakes for our view of major technology shifts and the long run evolution of economies, not least evidenced in the lengthy and still ongoing debate on the driving forces of the industrial revolution and the origins of industrial capitalism (Crafts, 1985, 1995; Mokyr, 1990, 2009; Allen, 2009; Bottomley, 2014).

Upon examination, many theoretical accounts opt for emphasizing either a set of ‘positive’ driving forces to innovation, e.g. private returns to innovation and market demand, or ’negative’ factors, sometimes summarized in the, somewhat vague, claim that “necessity is the mother of invention”. In the canonical economic models, innovation is motivated by expected private returns to innovation, which are ensured to varying degrees by intellectual property rights, e.g. patent laws (see Nordhaus, 1969; Scotchmer, 1991; Moser, 2005, 2013) or induced by increasing market demand and user initiatives (Schmookler, 1962; Lundvall, 1985, 1988; von Hippel, 1994). Other frameworks view innovation as resulting from advances in the stock of knowledge (Arrow, 1962; Romer, 1990; Aghion and Howitt, 1992), useful knowledge (Mokyr, 2002), new technological opportunities (Klevorick et al., 1995) and the diffusion of general purpose technologies (Bresnahan and Trajtenberg, 1995; Lipsey et al., 2005). Emphasizing negative pressure, a strand of literature points to factor-price inducement (Hicks, 1932; Binswanger et al., 1978; Popp, 2002), declines in profits (Antonelli, 1989; Greve, 2003b) and innovation as resulting from problem solving activity, or the overcoming of imbalances and technical obstacles (Dahmén, 1942; Dahmén, 1988; Rosenberg, 1969; Sahal, 1985; Dosi, 1988).

Along these lines, authors have also proposed competing hypotheses about the ‘when’ of innovation, ever since Schumpeter (1939) suggested the arrival of innovations in cycles of different length. Some authors have proposed that basic innovations are likely to be spurred by the adversities of economic crises (Archibugi and Filippetti, 2011; Berchicci et al., 2014) or the downturns of long waves (Mensch, 1979; Kleinknecht, 1987). Others have proposed that innovations are more likely to be spurred by increasing demand (Geroski and Walters, 1995; Brouwer and Kleinknecht, 1999), and positive prospects in the recovery from deep downturns (Clark et al., 1981; Freeman et al., 1982; Freeman and Perez, 1988).

The gist of the problem is that while neither of these views have a hard time finding support in economic history, neither of the views are exempt from criticism. Moreover, micro- or macro-econometric tests of relationships between innovation and economic activity (see e.g. Geroski and Walters, 1995) are typically only able to give support to one or the other hypothesis, while in fact innovation is likely to be simultaneously affected by a number of factors. Such issues have led

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some recent contributions to argue for the development of an inclusive approach which spans both negative and positive factors, acknowledging both external driving forces and the "internal" impact of innovations on the course of technological development (Arthur, 2007; Antonelli and Scellato, 2011; see also Mokyr, 2010). Turning this suggestion into an empirical research strategy, such an inclusive approach requires that factors behind innovation be studied both systematically (i.e. assembling large amounts of data) and in their proper historical setting (i.e. accessing the minute details of history). However, historical studies of the driving forces of innovation have mostly been carried out in terms of case studies.

This paper carries out, for the first time, a long-term study of the driving forces of innovation in Sweden during the third industrial revolution, 1970–2007. A first aim of this study is to give a systematic description of the historical driving forces of innovation and an account of the 'when' and 'how' of innovation. More specifically, we inquire into what driving forces explain patterns of innovation activity, and in turn, what factors and historical processes explain the prevalence of certain types of creative response across industries and over time.

Since the first stumbling block of a comprehensive empirical analysis is to distinguish analytically between different driving forces within an inclusive consistent framework, a second aim of this study is to synthesize ostensibly conflicting claims in previous literature into a coherent framework. Hence, Section 2 is devoted to the elaboration of a theoretical approach based on the view of innovation as an adaptive combinatorial search process and the view of innovation as a creative response to particular events and discrete inducements (Schumpeter, 1947; Antonelli, 2015). This framework amounts to suggesting four types of sources of incentives to innovation: "problems", "technological opportunities", "market opportunities" and "institutionalized search for improved performance".

The theoretical approach is subsequently applied in a study of driving forces to innovation during the third industrial revolution, drawing on a new micro-database containing in its entirety more than 4000 significant product innovations commercialized in Sweden between 1970 and 2007 (Sjöö et al., 2014; Sjöö, 2014; Taalbi, 2014; the empirical sections are further elaborations on chapter 4 in Taalbi, 2014). Data on innovation output has been collected from the screening of 15 trade journals covering the manufacturing sector, enabling both a quantitative study of innovation launches as well as detailed textual evidence on innovation biographies. This data is put to use to assess the patterns in the aggregate rate of innovation in the Swedish manufacturing sector and to classify and describe innovations according to economic, social and technological factors that have led to or contributed to their development. The underlying methodology is described in Section 3. Sections 4 and 5 present a statistical and historical analysis of the driving forces conveyed by this database. The statistical analysis examines the driving forces to innovation and carries out basic tests of cross-industry differences and other covariates to explain patterns of creative response. To assess the relationship between innovation activity and cycles in economic activity, a bandspectrum regression is employed. The historical analysis details the specific economic, social and institutional circumstances that explain the basic patterns of innovation as creative response. Section 6 concludes.

2. A framework of innovation as creative response

To a student of technology wishing to approach the empirical subject-matter of the driving forces of innovation, the available literature can be quite overwhelming. Arguably, there is an apparent need for a coherent framework for analysis of the driving forces of innovation, which covers a broad range of both positive and negative factors. Common ground for the diverse accounts of the evolution of technology can certainly be found in Schumpeter's "The creative response in economic history" (1947), distinguishing between 'adaptive response' and 'creative response' (see also Antonelli, 2015). The former term denotes measures taken within the "existing practice" of an economy, industry or firm, whereas the latter denotes measures taken "outside of the range of existing practice", viz. innovation (Schumpeter, 1947, p. 150). Schumpeter wrote that creative response rarely, if ever, is fully understood *ex ante*, i.e. cannot be predicted from "pre-existing facts". The 'how' of the mechanisms behind creative response "must therefore be investigated in each case" (Schumpeter, 1947, p. 150). An understanding of innovation as creative response should thus leave plenty of room for history. The aim of the current endeavors is therefore to elaborate a theoretically grounded classification of sources of innovation that can be put to use in empirical analysis.

The view proposed here recognizes first of all that technological objects are combinations of other technological objects and that innovation is a *new* combination (Schumpeter, 1911; see also Weitzman, 1998, Fleming and Sorenson, 2001 and Arthur, 2009). Accordingly, not only does any innovator face a more or less complex combinatorial problem, but the evolution of technology must be thought of as the evolution of a complex system. The full implication of this principle is a relational outlook where technologies must be viewed as (co-)evolving in greater or smaller constellations forming technological systems (Gille, 1978; Hughes, 1983, 1987; Nelson, 1994) or development blocks (Dahmén, 1950; Dahmén, 1988), in which opportunities, pressures and imbalances emerge.

Of course, the possible combinations of technological objects are ample, unfathomably so, and innovations can in principle be discovered by any agent that engages in search. But the question of interest is under what circumstances there are incentives to take the risk of deploying resources into such search activity. On this matter, we accept the basic formulation of Schmookler (1962, p. 19), that "the incentive to make an invention, like the incentive to produce any other good, is affected by the excess of expected returns over expected costs". This is to say that economic agents search for new combinations only when they have reason to believe that returns from innovation exceed the costs of search. This makes the incentives to innovation a question of information, typically limited and imperfect. In general, *depending on the complexity* of the combinatorial problem, let alone market and product uncertainty, innovators can to a higher or lower extent predict the consequences of their choices. Typically, innovators are acting under fundamental uncertainty (Alchian, 1950) and are boundedly rational and myopic (Cyert and March, 1963; Simon, 1991). For this reason, firms use focusing devices (Rosenberg, 1969) and procedures (Nelson and Winter, 1982) to make the choice of when and how to innovate.

Since the degree to which innovators respond to economic factors is fundamentally linked to the complexity of the combinatorial problem, this study proposes, following some recent contributions (see e.g. Arthur, 2007, 2009; Antonelli, 2011) to combine insights from the economics of complexity, with the notion of innovation as responding to changes in economic data.

To this end this framework builds on the nowadays standard NK-model, originally introduced to describe adaptive genetic evolution on fitness landscapes (Kauffman and Levin, 1987; Kauffman, 1993), but subsequently applied to e.g. economics of innovation to describe how search strategies – local search or distant search, exploitation or exploration – are afflicted by the complexity of the space of combinations (cf March, 1991; Levinthal, 1997; Frenken, 2000). Recent research has remarked that the NK-model is an apt tool for understanding how complexity shapes search strategies of firms, but that notions such as problemistic search and negative feedback have not been properly included (Gavetti et al., 2012; Billinger et al., 2013). The current endeavors examine a way to link the NK-model to the notion of innovation as a creative response to changes in economic data.

2.1. Opening up the black box

How can we understand the process through which agents find "better" combinations? With Brian Arthur (2007, p. 275) "invention is a process of linking some purpose or need with an effect that can be exploited to satisfy it" and "[t]his linking is a process, a lengthy one of envisioning a concept – the idea of a set of effects in action – and finding a combination of components and assemblies that will make the concept possible" (Arthur, 2009, p. 204). Elaborating on these insights, an innovator faces two puzzles (*αίνιγμα*):[1]

(a) to find out how to attain certain characteristics in a product by combining available input modules
(b) to identify those characteristics of a product that have high value, or payoffs.

The task of finding combinations of input modules to attain a certain performance in terms of characteristics may be called the "*S-puzzle*". The puzzle of connecting characteristics to high values may be called the "*Z-puzzle*". The innovator thus must find out what characteristics of the product have high payoffs and what combinations of inputs correspond to the desired outcomes (see Fig. 1).

2.1.1. Payoffs and costs

Now, if, following Schmookler, there are incentives to innovate when expected payoffs from innovation are larger than expected costs, we must relate payoffs and costs to these fundamental puzzles involved in any innovation process. We suggest to think of the payoffs of this two-step combination puzzle in terms of an NK model (Kauffman, 1993; Levinthal, 1997; Kauffman et al., 2000; Frenken, 2000, 2006). Conventionally, NK models map the choices of input modules S to actual payoffs π. For example, an airplane can be described by its components including the engine, control system, etc. Each of these N modules has a number ν_i of known design options, e.g. the type of aircraft engine. Innovators create new product varieties by combining input modules, with varying results in terms of product characteristics and payoffs. Formally, to achieve goods with certain characteristics, the firm combines designs s of the N modules $i \in \{1, \ldots, N\}$,

$$s_i \in S_i \tag{2.1}$$

where S_i is a set $\{0, 1, \ldots, \nu_i\}$.[2] Thus, the design choices made are represented as a vector $\mathbf{s} \in \prod_i^N S_i$ and the size of the search space for a firm is[3]

$$\prod_i^N \nu_i \tag{2.2}$$

It is clear that the complexity of the puzzle depends on the number N of input modules that have to be combined. Low complexity products consist of only a few components, and high complexity products have many components. However, the complexity of the puzzle is also determined by the degree to which input modules interact with each other. Conventionally, in the NK-model framework, each module vector $\mathbf{s}$ corresponds to a fitness value. In our framework, the fitness value can be understood as a particular characteristic dimension, such as the power and fuel combustion of an engine, and so forth. The fitness value is written as the average of the modules' fitness contributions:

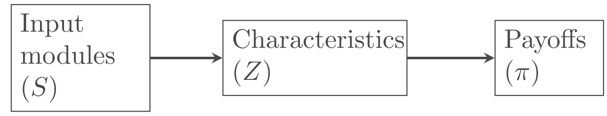

Fig. 1. The S- and Z-puzzles.

$$z = \frac{1}{N}\sum w_i(s_i; s_{i_1}, \ldots, s_{i_K}) \tag{2.3}$$

where $w_i \in [0, 1]$ are drawn from a uniform distribution. These random numbers are functions of the design choice of the module i and the design of K other modules, with which the module i interacts. As it were, such "epistatic" (the term for interacting genes) components impose conflicting constraints, which is an important source of imbalances and complementarities between technologies. With low K the fitness landscape is smooth (Fig. 2a) and the agent can find the local optimum by "hill-climbing" or trial-and-error, i.e. modifying one or a couple of s_i at the time (Kauffman, 1993), what has been called "local" search (Nickerson and Zenger, 2004). With higher K the number of optima increases and it becomes more difficult to improve the fitness contribution of one element without decreasing the fitness of another. The landscape thus is rugged (Fig. 2b) and agents are more likely to employ heuristics to search sub-areas of the landscape (Nickerson and Zenger, 2004). Such heuristics may be linked to to *technological paradigms*, pace (Dosi, 1982) which embody strong prescriptions and selections of what problems (*αίνιγμα*) to pursue and what input modules to change.[4]

This formulation must however be complemented with the fact that innovators also look for combinations of product characteristics that have high payoffs. Here we are satisfied with assuming that payoffs are roughly a linear combination of a number of characteristics z indexed k that are relevant for the product:

$$\pi = \sum_k \pi_k = \sum_k \beta_k z_k + \epsilon \tag{2.4}$$

where ϵ is a stochastic variable over the characteristics space and where we note that characteristics z_k of a given product may have negative payoff contributions, which decrease the overall payoffs. I wish to draw attention here to two things of importance. First, it is clear that the predictability of the *Z*-puzzle can be high or low. At this juncture it depends on the variance of ϵ, ranging between entirely unpredictable payoffs if the variance is high, and entirely predictable if the opposite is true. Thus, payoffs are not necessarily predictable from characteristics and it is far from always clear what combination of characteristics would solve a given problem – the complexity of pharmaceuticals and vaccines come to mind. In other situations, there is a strong selection for characteristics, and hence a strong correlation between characteristics and payoffs, that induce an unambiguous direction of technological change, akin to Dosi's (1982) "technological trajectories". Thus, while technological paradigms focus the S-puzzle to a subset of search space, strong correlation between payoffs focus search to certain characteristics dimensions (e.g. fuel consumption). Secondly, payoffs and payoff contributions of certain characteristics change over time due to factors *external* – e.g. prices or demand – or, importantly, *internal* to the process of technological change. An example of the former is a shift in prices, or evolving customer requirements. An example of the latter is the introduction of new innovations, which create demand for a particular characteristic, or render some characteristic obsolete. Accordingly, one cannot lose sight of the fact that payoffs may reflect technological requirements elsewhere.

We now have an idea of how payoffs relate to the basic S- and Z-puzzle. Search costs on the other hand depend on innovators' conception of the search space. We remind ourselves that the task of the innovator is to find a combination of inputs that yield a particular set of output

[1] The frequently confusing ways in which words such as "problem" and "puzzle" etc. are used in the literature make it difficult to emphasize an important distinction between two entirely different situations that typically face innovators: "problems", or enigma, that are based on an epistemological uncertainty, for example, an engineering or mathematical problem, and the more particular type of "problem" that comes with a value attached, i.e. a fact which is unsatisfactory or inconvenient in relation to expectations, requirements or standards. Though perhaps somewhat obscure, a wordplay in Greek could alleviate this distinction. While the Greek *αίνιγμα* (aínigma, 'riddle') is commonly understood as a problem with epistemological root, the Greek *άνοιγμα* (ánoigma, 'opening', 'leak' or 'gap') can be used to refer to a problematic difference or gap.

[2] Formally, a zero value should be taken to mean that a type of input module i has not been discovered yet.

[3] In the simplest case, $\nu_i = 2$, $\forall_i$ and the size of the search space is 2^N.

[4] With (Dosi, 1982, p. 152) technological paradigms are "a 'model' and a 'pattern' of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies."

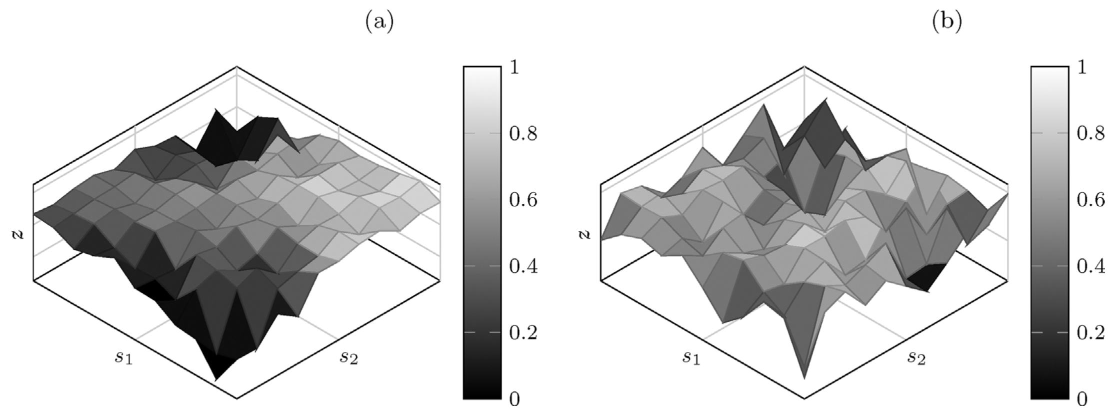

Fig. 2. Smooth (a) and rugged (b) fitness landscape for two epistatically related input modules s_1 and s_2.

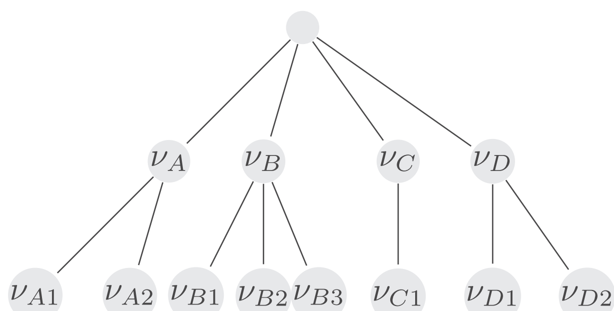

Fig. 3. Two layers of combination problems. ν denotes the number of design options of module *k*.

characteristics, which attain higher payoffs. This search is not blind, but guided by search routines, "theories", procedures and engineering knowledge of how characteristics of inputs correspond to output characteristics. Now, we say that the knowledge and heuristics of would-be innovators defines a *technological distance* (cf Kauffman et al., 2000), as the number of input modules that (they believe) have to be modified to find a solution with characteristics *z*. At this juncture, this notion is meant in an entirely *subjective* sense: different agents may have different heuristics, theories and knowledge about the number of modules that should be modified (and which ones too). Moreover, technological paradigms may cause agents to have a strong common sense of heuristics, but the advancement of science and changes in technological paradigms will change perceptions of technological distance over time, and so technological distance is essentially an artefact of the historical process of interaction between local learning, generic scientific and technological advances and feedback from the economic environment.

We must however note a few fundamental properties of technological distance that are linked to the character of technologies. First, since some inputs required may not be available, but too must be invented, the technological distance may involve several layers in the production chain. If we think of the production chain as a tree, the technological distance is thus the number of *roots* that have to be modified to discover a new technology (Fig. 3). Moreover, a generic facet of technological distance is observed from the history of technology if we ask: why is it that humans most often have stumbled upon relatively crude and simple inventions before being able to refine and improve them? The answer to this question, I think, has a lot to do with complexity: the number of available inventions required to construct an airplane is larger than the number of inventions required to invent the wheel, and what is more, improvements in airplane technology take place by way of increasing complexity of its components. This is to say that large improvements are likely to involve a modification of a large number of components and that we are less likely to find by random chance a combination of products which is much superior, than an

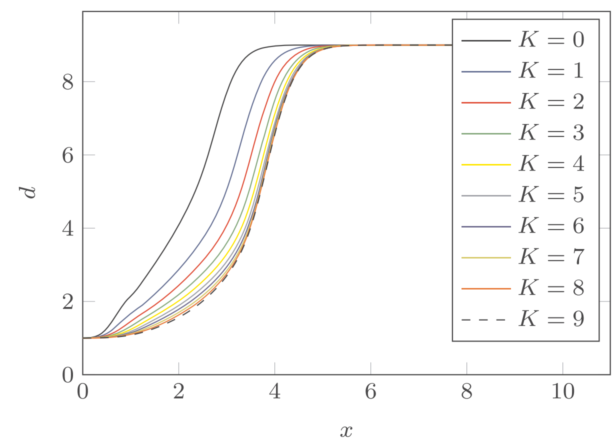

Fig. 4. Average search distance (d) to characteristics $z \geq x$ in an *NK*-type model with $N = 10$. Note: For the underlying considerations and further comments, see Appendix A.

inferior combination of products. Technological distance increases with the distance in characteristics of the product. This principle can be shown as a result from the standard NK model (Fig. 4).

Accordingly, it is fair to assume that subjective technological distance is increasing as the distance of the characteristics sought for increases. What is important for our framework is that the subjective technological distance also translates into an idea of the size of the search space and the search costs. The search costs, are proportional to the size of the search space with research costs per trialed combination and a factor that expresses the degree to which the space can be reduced into a smaller search space by decomposing it into sub-problems (see Simon, 1962, 2002; Frenken, 2006). Accordingly,[5]

$$C(\mathbf{z}) = \frac{1}{2} R \mathscr{D} \prod_a \nu_a(\mathbf{z}) \tag{2.5}$$

where R are research costs per trial, $0 \leq \mathscr{D} \leq 1$ expresses the decomposability of the search space, and $\prod_a \nu_a$ is the size of the search space, as determined by heuristics and know-how, which is increasing in the distance to z from the set of currently known characteristics.[6]

[5] We expect that on average, half of the search space has to be searched.

[6] With N input modules and ν_i alternatives for each module i, the size of the searched space is $\prod_i^N \nu_i$. If the space is *decomposable*, there is a number L of non-overlapping subsets of the set of input modules $I = \{1, \ldots, N\}$. These subsets can be searched separately. Denote these $\Lambda_l \subset 1, 2, \ldots, N$ enumerated $l \in 1, 2, \ldots, L$. These are partitions of the set I, i.e. non-overlapping and the union of all subsets is I: $\forall_{l \neq m},\ \Lambda_l \cap \Lambda_m = \varnothing$ and $\bigcup_l \Lambda_l = I$. We can express the number of combinations to be trialled in a sub-problem l as $\prod_i \nu_{i \in \Lambda_l}$. The ratio of the decomposed space size to the total space size gives an indicator $\mathscr{D}$ of the decomposability of the space: $\mathscr{D} = \frac{\sum_l \prod_i \nu_{i \in \Lambda_l}}{\prod_i \nu_i}$

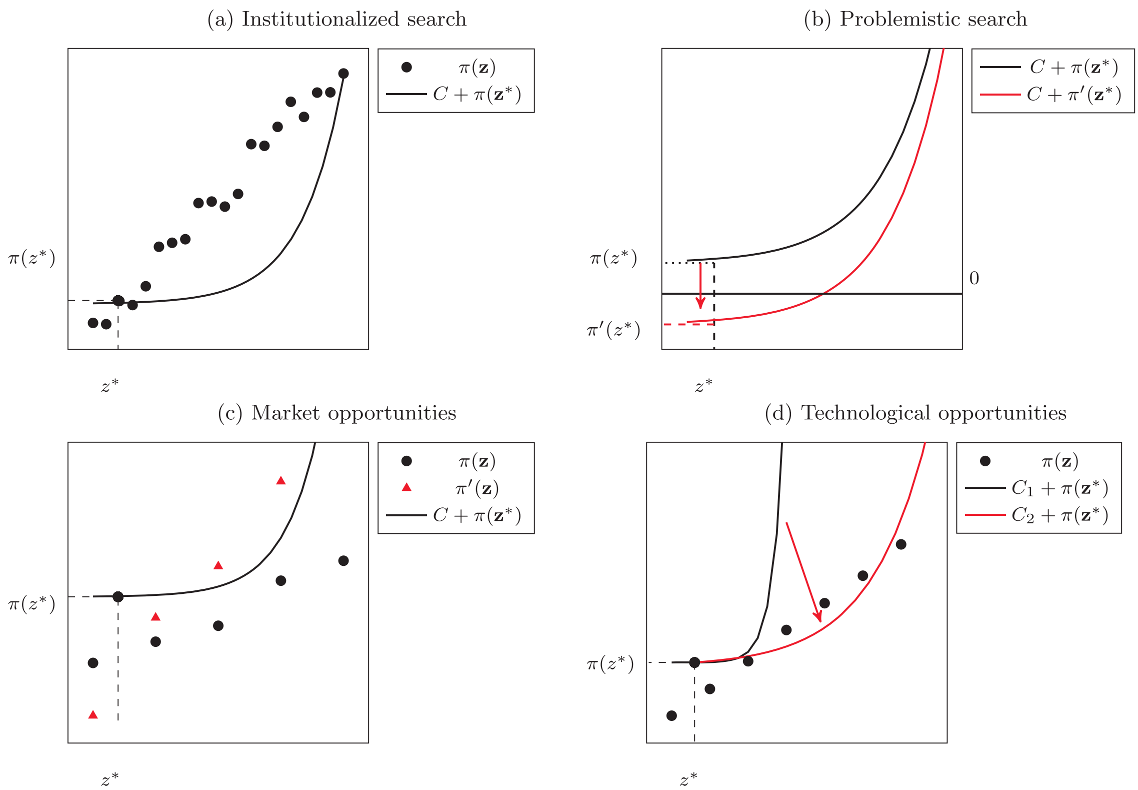

Fig. 5. Illustration of driving forces to innovation (payoffs and costs on *Y* axis, characteristics on *X* axis).

2.1.2. *Four driving forces of innovation*

The Schmooklerian view that there are incentives for search whenever anticipated payoffs from search are larger than expected search costs, can now be formulated as functions of a vector of characteristics **z**. Given their information on payoffs $\pi(\mathbf{z})$ for some characteristics **z**, the current best-practice payoffs $\pi(\mathbf{z}^*)$ and the search costs for some characteristic z, $C(\mathbf{z})$, agents have incentives to search whenever the increase in payoffs is larger than expected search costs, i.e.

$$\pi(\mathbf{z}) - \pi(\mathbf{z}^*) - C(\mathbf{z}) > 0 \tag{2.6}$$

Together with our previous considerations, this equation offers a straightforward framework for understanding the driving forces of innovation in terms of four states of affairs, or to be precise, information or heuristic knowledge about the states of affairs. These are pictured (albeit simplified) in Fig. 5a-d, where there are incentives for search whenever agents know of payoffs $\pi(\mathbf{z})$ that are larger than current payoffs $\pi(\mathbf{z}^*)$ plus expected search costs (C). Since agents face varying degrees of complexity and uncertainty, the payoff and cost functions are more or less patchy and incomplete. Hence, the four different search strategies may be connected to varying levels of complexity and uncertainty about payoffs and the space of input combinations.

In a first situation (Fig. 5a), there are generic incentives for innovation, that is to say, Eq. (2.6) holds for a large number of known characteristics **z**. The term "institutionalized" is taken to denote that there is both ample means for innovation by way of routinized R & D and that payoffs express significant technological, social and economic forces towards a direction of technological change (compare Dosi, 1982; MacKenzie, 1993; Greve, 2003b). Payoffs are (approximately) known for a large set of characteristics, and there is a strong direction of technological change. In Fig. 5a, there are incentives for innovation as long as the returns from innovation are larger than the current payoffs plus expected search costs. This situation conforms well to the phases of industry life cycles when product uncertainty decreases and there is a "dominating design" (cf Utterback, 1994). This situation is also analogous to Kuhn's 2012 [1962] "normal science" and related to Dosi's "technological trajectories" to the extent that the direction conveyed by expected payoffs reflect strong selection towards a certain set of characteristics (and not other sets of characteristics). As such, it is not hard to imagine an instantiation of Fig. 5a in Moore's law, the astoundingly rapid decrease in size and transistor counts of microprocessors.

When this is not the case, hindered by market uncertainty or considerable complexity, pushes for innovation emerge discretely. As it were, innovators respond to three major types of *focusing devices*, pace Rosenberg (1969), which enable innovators to identify links from sets of input combinations to high payoff solutions: problems (*άνοιγμα*), market opportunities and technological opportunities. These three focusing devices correspond to shifts in the knowledge about current payoffs of a product, the possible payoffs and the search costs, respectively, which can be introduced either by changes *external* to the development of new technologies, such as changes in economic data and scientific advance, or *internal* to them, i.e. being the results of the introduction of previous innovations.

Facing considerable uncertainty on payoffs – i.e. a highly complex and rugged *Z*-space, in which there is no predictable feedback from varying characteristics - information of high value regions is rather more likely to be obtained from information on problematic gaps or imbalances. A problem (*άνοιγμα*) is a dissatisfaction with the current state of affairs, which is intuitively understood as an observed negative payoff contribution of the characteristics of a product, i.e. a characteristic that decreases the total payoff of the product. The attainment of knowledge of such problems is in general linked to those aspects of the process of economic development which decrease current payoffs or payoff contributions of some characteristic, or which bring to the attention of agents an insatisfactory performance. The decrease in current payoffs in Fig. 5b induces search for solutions, if engineers or innovators can conceive of a set of characteristics that provide a feasible solution. Such a decrease could be caused by several changes in the state of affairs. One source of such gaps is changes in economic data, namely that a firm must adapt to a new situation in which a product is no longer profitable or competitive. This mechanism for innovation has been called failure inducement or negative performance feedback (Cyert and March, 1963; Antonelli, 1989; Greve, 1996, 2003a,b). A pivotal internal source of such gaps is the emergence of *technological imbalances*, the situation when the insufficient performance of a product *A* limits or hampers the use of an innovation *B* (Rosenberg, 1969; Hughes, 1983, 1987), being a strong incentive for improvement in *A*.[7]

Market opportunities emerge due to changes in factor prices or in consumer tastes, through user requirements or simply through the discovery of an unexploited market demand. In our framework, this is equivalent to a shift in the known payoffs (Fig. 5c), or equivalently, an increment in the set of information on payoffs. Like problem-driven innovation, market opportunities and producer-user interactions are likely to be more salient important of innovation when there is uncertainty about high payoffs (see e.g., Mowery and Rosenberg, 1979; Lundvall, 1988; von Hippel, 1988; Fontana and Guerzoni, 2008). These suggestions are well in line with Schmookler and other scholars, arguing that changes in consumer preferences (Mowery and Rosenberg, 1979), and general demand factors provide pivotal incentives for innovation by raising expected returns from innovation (Schmookler, 1962; Geroski and Walters, 1995; Brouwer and Kleinknecht, 1999).

Lastly, facing considerable uncertainty about what combination of input characteristics to look for, i.e. a high complexity S-puzzle, heuristics are necessary to restrict search to a subset of the S-space, thus reducing the expected search costs. As a last source of innovation, we thus find new knowledge or technological opportunities that are able decrease expected search costs. Specifically, this mechanism works by *decreasing the technological distance* to some known set of high payoff characteristics, or focus the search to a subset of the space of input combinations. The decrease in costs in Fig. 5d could be caused by a range of factors. In general, any factor that shift the knowledge of an agent or the content of technological paradigms is likely to decrease search costs: e.g. new scientific advances, learning by doing, etc. Of course, some of the most salient sources of such shifts have been other innovations, in particular general-purpose engines or technologies, such as electricity, electric or combustion engines and microprocessors (Bresnahan and Trajtenberg, 1995; Helpman, 1998; Lipsey et al., 2005).

3. Methods and data

Lack of consistent large scale data on innovation output has effectively made difficult the systematic empirical study of innovation activity and its driving forces for longer periods of time. This study employs newly constructed micro-data (Sjöö et al., 2014) of innovation output to examine driving forces of innovations across the Swedish manufacturing industry during the third industrial revolution. Specifically, the database, called SWINNO (Swedish Innovations), covers product innovations[8] launched in the Swedish manufacturing industry and business services (including software, supply of telecommunication network services and technical consultancy).

The database is based on the literature-based innovation output approach (see Kleinknecht and Bain, 1993). Over 4000 innovation objects have been registered through the reading of 15 trade journals for the period 1970–2007, covering the manufacturing industry and business services. The edited sections of journals were scanned for innovations, defined as an entirely new or significantly improved good, process or service in economic use or sold on a market. Moreover, only innovations developed by Swedish companies were included, in part because the editorial mission of the trade journals is more or less confined to the Swedish industry.

Of the innovation projects found, 3377 innovations were commercialized and described in edited articles written with an innovation focus, i.e. written to introduce the innovation.[9] Trade journal articles provide detailed information on the innovating firm, as well as descriptions of the development and commercialization of individual innovations. This information has been used to produce time series of the commercialization of innovations and to classify innovations according to economic, social and other factors that led to or contributed to their development. Thus, it is possible to simultaneously assess when innovations were launched, and the types of problems and opportunities that drove their development.

3.1. Methodological considerations

The methodology of the database rests upon the rationale that one of the editorial missions of trade journal editors is to publish articles on innovation activity with relevance to the industry. This means that the innovations contained in the database are a subset of the total population of innovations. Rather, the aim of the methodology is to cover significant innovations, expected by editors to be of importance, rather than small product variations.

Several measures have been taken to assess the methodological robustness and the character of the data. Interviews with journal editors have confirmed the assumption that journals aim to report on innovations believed to be of importance to the industry (see Sjöö et al., 2014). Moreover, these interviews have confirmed that material on innovation is not crowded out due to lack of space.

The sensitivity of empirical results with respect to the selection of journals has also been analysed, in part through interviews with editors and in part through formal sensitivity analysis. Interviews confirmed the absence of significant editorial inconsistencies of the journals. In an econometric test we found the aggregate count of innovations over time and across industries to be robust to exclusion/inclusions of individual journals (see Sjöö et al., 2014). Comparisons with other constructed datasets of major innovations confirm a reasonably large overlap, which strengthens the interpretation that the database captures more important innovations.[10]

Hence, the database can be said to capture innovations expected to be significant to the industry. It is important to stress that our empirical analysis does not analyze incremental innovations, but rather major improvements in products or technology. The data being as such, in keeping with the framework sketched above, one may expect search strategies associated with low complexity, such as institutionalized search, to be less pronouncedthan they would be if incremental innovations had been included.

3.2. A classification of origins of innovation

The framework sketched above suggests four broader types of incentives that spur innovation activity: institutionalized search, market opportunities, technological opportunities and problem-driven search. The classification of innovations into these categories has been based

[7] With Nathan Rosenberg: "The relationship among components was usually such that some imbalance *had* to be corrected before an initial innovation could be fully exploited. Such a situation therefore continually directed the attention of technically competent personnel to the solution of problems of obvious practical importance" (Rosenberg, 1969, p. 11, original emphasis).

[8] A product innovation is in the database defined as any innovation that is being traded on a market, in contradistinction with process innovations, defined as innovations being withheld from markets and applied in-house only (Sjöö et al., 2014).

[9] The selection made is motivated to reassure data quality. Other types of articles were reporting innovations in passing, or as brief mentions of new products presented at industrial fairs.

[10] Two lists of major innovations have been produced for Sweden for the period studied. A first publication, Wallmark and McQueen (1991) listed the 100 major innovations in Sweden, 1945–1980. Out of those launched after 1970, 74% were also found in SWINNO. A publication by the Swedish Institute, based on expert opinions, lists major innovations of which 86% were also covered in SWINNO during the period 1970–2007.

Table 1
Classification schedule of origins of innovations.

Origin of innovation	*Description*
Institutionalized search	Innovation is developed only to improve characteristics along known performance trajectories
Market opportunities	Innovation is developed to address customer requirements or an unexploited market niche
Technological opportunities	Innovation is enabled and developed due to the forthcoming of new technologies or scientific advances
Problems	Innovation is developed as a response to economic, environmental, organizational, techno-economic or other problems

upon direct textual evidence of descriptions of the innovation. The first category, is operationalized in contradistinction to the others as innovations which are only developed to enhance the performance of a product. The second category is operationalized as innovations that are developed to accommodate particular customer requirements and responses to specific market opportunities, which did not originate in the observation of a problem.[11] The distinction of innovations that exploit technological opportunities is based on explicit mentioning in the journal articles of a technology or scientific discovery which contributed to or enabled the development of the innovation.

An operational definition of a problem may in some cases lie close to the notion of obstacle, i.e. a factor which impedes the attainment of some firm-specific, industrial or societal goal. In other cases the description of the innovation process allowed for the distinction of a factor, which the firm managers perceived as a problem that needed to be solved. An innovation was considered problem-solving if the development of the innovation was explicitly described as aiming to overcome an obstacle or problem as defined previously. For the problem-solving innovations a note was taken of this textual evidence, which has served as the basis of qualitative descriptions of innovation activity

A further distinction among different types of problems is motivated. Table 2 presents five categories of problems that have been found to drive Swedish innovations. A set of innovations have been developed as a response to *economic problems*, emerging from changes in factor prices, profits, or obstacles to the rational production and use of goods. Second, there are innovations that have responded to environmental regulations and broader environmental problems stemming from negative externalities (cf Grübler, 2002 and Requate, 2005). These problems are labelled *environmental problems*, i.e. the negative effects of industrial production affecting a third party (other than the producer and consumer of a good). Third, one may distinguish innovations responding to demands pertaining to the work environment. These sets of problems have been labelled *organizational* problems, as they typically reflect intra-firm and broader social conflicts. A fourth category is “technological bottlenecks”, which refers to techno-economic obstacles to the exploitation of a new technology, product, market or some other opportunity. As opposed to bottlenecks in the production of goods (a production bottleneck), this refers thus to a bottleneck in the exploitation or development of a new technology.

3.3. Other variables used

Five other variables used in the empirical sections are based on the qualitative information from the journal articles, summarized in Table 3. The innovations found in the journal articles were given a commercialization year as described in the article and categorized according to the Swedish Industrial Classification system 2002 (SNI 2002) corresponding to ISIC Rev 2 (henceforth referred to as ISIC).

The three other variables are of interest in the current study, since they link the creative response to important facets of search in fitness landscapes. The variable “explorative” indicates the novelty of the innovation from the firm perspective. An innovation was judged as explorative, as opposed to exploitative (March, 1991), if the firm ventured into a new field of technology and the innovation required a significant reconfiguration of the firm's knowledge base. This also includes cases when the firm was started to commercialize the innovation. The innovations were also classified as “new to the world” as judged from explicit textual evidence in the articles. The variable “complex system” refers to the architecture of the innovation and was classified on the basis of description of the function and composition of the product.

4. Innovation and creative response in the Swedish manufacturing industry

The empirical results, shown in Fig. 6 and Table 4, convey that the clearly most important sources of innovations were problems and new technological opportunities, whether stemming from scientific advances or the diffusion of general-purpose technologies such as microelectronics. 69.6% of all the innovations developed cited such problems or opportunities, accounting for 45.0% and 40.9% respectively.

Fig. 6 suggests that innovations driven by new opportunities have followed a particular pattern of two major shifts. A first increase took place from 1970, culminating in 1983. The vast majority of these innovations were enabled by the application of microchips, minicomputers and microelectronics. These innovations were largely focused on industrial applications and factory automation. Following the trough of the 1990s, new opportunities were unleashed, notably by the deregulation of telecommunication markets and the massive investment activity that arose around Internet infrastructure.

Innovations citing different types of problems were by and large concentrated to the economic and energy crisis of the 1970s. This pattern of creative response culminated in the beginning of the 1980s. Innovations responding to obstacles to the rational production, transportation or use of goods, as well as environmental innovations, were important in explaining the increase, as shown in Fig. 7. During the crisis of the 1970s, most of these innovations were responding to economic, environmental and organizational problems. Technological obstacles, notably connected with the expansion in telecommunications and Internet infrastructure, became a more important source towards the latter half of the period. There was also an increase in problem-driven innovations during the 1990s, e.g. automotive innovations responding to emission control regulations.

By contrast, the number of innovations driven by institutionalized search and market opportunities accounted for 13.53% and 13.95% respectively. This may be considered to question the hypothesis of demand-driven innovation. However, we may recall that our definition of market opportunities is conservative and referring only to those innovations explicitly developed to address customer requirements or an unexploited market niche. Indirect influence of market conditions may still be reflected in innovation activity, especially those driven by generic problems.

4.1. Regression analysis

Basic facets of the patterns of creative response can be further

[11] It is appropriate to note here that, without contradiction, a problem for one firm, industry etc. may be expressed as a market opportunity for another firm. In practice, in such instances the core driving force of innovation has been considered as the observation of a problem. This means that market opportunities here must be interpreted as being more limited than the generic definition offered in Section 2.1.2.

Table 2
Classification schedule of problem-solving innovations.

Problem area	*Examples*
1. *Economic* Techno-economic obstacles to the rational production of goods	Unprofitability, rising energy prices, irrational costs (e.g. material spill)
2. *Environmental:* Negative externalities	The handling of waste, replacement of environmentally harmful products
3. *Organizational:* Work-environment	Occupational noise, toxic welding gas
4. *Technological bottlenecks:* Techno-economic obstacles to the exploitation of a new technology, the production of a new good, or the opening of a new market	Capacity bottlenecks (e.g. insufficient capacity of switching circuits), Insufficient performance of technological components
5. *Miscellaneous:* Industry or firm-specific problems	Medical technical problems, idiosyncratic firm problems

Table 3
Description of other variables used.

Variable	Description
Commercialization year	Year of commercialization of the innovation according to journal article.
Product type	The product code (ISIC Rev 2) of the innovation.
Explorative	The innovation is entirely new from the perspective of the firm (Y/N).
New to the world	The innovation is described as new to the world market (Y/N).
Complex system	The innovation is a complex system consisting of a large number of components (Y/N).

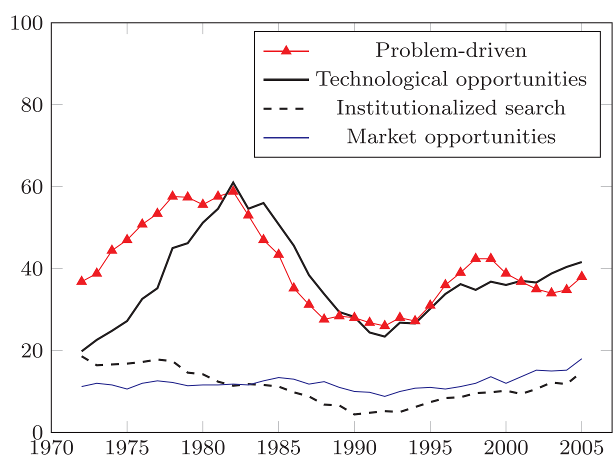

Fig. 6. Innovations by origins (5 year centered moving averages), 1970–2007. *Note*: Due to overlaps the sum of opportunity, problem-driven and institutionalized search may not add up to the total.

Table 4
Count of innovations by origin in problems, market and technological opportunities and institutionalized search.

	1970–1989	1990–2007	1970–2007
Problems	901 (46.85%)	616 (42.37%)	1517 (44.92%)
Technological opportunities	772 (40.15%)	607 (41.75%)	1379 (40.84%)
Institutionalized search	283 (14.72%)	174 (11.97%)	457 (13.53%)
Market opportunities	237 (12.32%)	234 (16.09%)	471 (13.95%)
TOTAL	1923	1454	3377

Note: Due to overlaps the sum of opportunity, problem-driven and institutionalized search may not add up to the total.

illuminated through examining covariates of the tendency of innovations to be driven by problems and opportunities. Are there significant differences in the tendency of innovations to be driven by problems, market and technological opportunities across industries and over time?

Table 5 examines the cross-industry importance of problem-solving and opportunities, while controlling for macro-economic covariates.

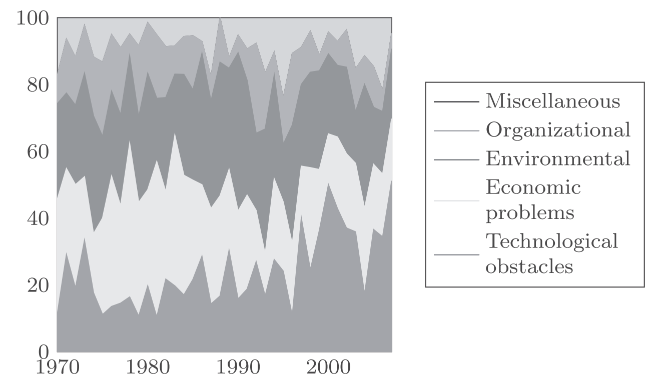

Fig. 7. Problem-solving innovations, by sub-category (% of total), 1970–2007.

Due to the varying hypotheses about the relationship between innovation and economic data, wavelet analysis is used to separate out short-run (2–8 years), medium-run (8–16) and long run cycles (16–32 years) in the annual growth of GDP (Percival and Walden, 2006; Andersson, 2008, 2016). Fig. B1 shows short-run, medium-run and long-run components of GDP growth. The long-run component is connected to "long swings" or Kuznets cycles (compare Schön, 2010; Andersson, 2016).

This test is allowed by a logistic regression where the dependent variable $y_{i,\mathscr{F}}$ is construed as being 1 if an innovation i cited a factor $\mathscr{F}$ as a driving force, otherwise 0. The model equation is

$$y_{i,\mathscr{F}} = \sum_j \alpha_j I_{ji} + \sum_k \beta_k Z_{ki} + \gamma_S x^S_{t-l} + \gamma_M x^M_{t-l} + \gamma_L x^L_{t-l} + \epsilon_i \quad (4.1)$$

where I_{ji} is a set of dummy variables for the industry class j of innovation i, Z_{ki} are covariates at the level of the innovation (novelty and complexity), and x^S_{t-1}, x^M_{t-1} and x^L_{t-1} are short, medium and long run cycles in the growth rate of GDP, with lag l from the year of commercialization.

The results (Table 5) inform of distinct patterns of creative response. Innovations driven by problems and technological opportunities are associated with higher market and firm novelty of the innovations, indicating a possible relation with explorative search strategies and disruptive innovation processes. In general, technological opportunities were associated with innovation in complex systems. The results also illuminate the presence of important differences in creative response across industries. The industry dummies compare the driving forces in the high tech and medium high tech industries with medium-low and low tech sectors as baseline, following standard industrial classifications for ISIC Rev 2 (OECD, 2001). Overall, innovations in high-tech and medium high-tech industries were more likely to be driven by problems or opportunities. ICT industries (computers, telecommunication equipment, measuring and optical instruments and software), machine-tools and pharmaceuticals have been driven to a large extent by new technological opportunities. Conversely, problem-solving innovations are more common in medium high-tech industries, notably machinery, chemical products (except pharmaceuticals) and automotive transport equipment, and less likely among ICT products such as

Table 5
Logit regressions (marginal effects) for problem and opportunity driven innovations.

Variables	(1) Problems	(2) Tech. opp.	(3) Market opp.
Innovation			
New to the world	**0.301*****	**0.600*****	**-0.433*****
	(0.0912)	(0.0963)	(0.139)
Explorative	**0.331*****	**0.469*****	0.119
	(0.0797)	(0.0844)	(0.111)
Complex system	**−0.317*****	**0.250****	**−0.395****
	(0.102)	(0.108)	(0.160)
GDP growth			
Short-run$_{t-4}$	−1.238	1.633	−2.575
	(1.838)	(1.977)	(2.673)
Medium-run$_{t-4}$	**10.46****	−8.103	4.479
	(5.039)	(5.420)	(7.179)
Long-run$_{t-4}$	**-19.64*****	**-29.90*****	**26.52*****
	(7.448)	(7.961)	(10.11)
High-tech			
Pharmaceuticals	**−1.547*****	**1.919*****	−0.833
	(0.401)	(0.357)	(0.536)
Computers	**−0.421****	**2.416*****	**−0.977*****
	(0.164)	(0.186)	(0.270)
Telecommunication eq.	**−0.350****	**1.188*****	−0.158
	(0.153)	(0.157)	(0.192)
Measuring & optical instr.	**−0.267****	**1.697*****	**−0.905*****
	(0.117)	(0.127)	(0.181)
Chemical products	**1.020*****	0.185	**−1.059****
	(0.265)	(0.272)	(0.436)
Software	**−0.608*****	**1.677*****	−0.202
	(0.170)	(0.172)	(0.205)
Aircrafts & spacecrafts	**−2.076****	0.509	**1.032***
	(1.045)	(0.579)	(0.582)
Medium-high-tech			
Machinery for mech. power	**0.510****	−0.0149	−0.377
	(0.210)	(0.245)	(0.294)
Furnaces & furnace burners	**1.287*****	0.529	–
	(0.367)	(0.357)	
Lifting & handling eq.	−0.246	**0.618*****	−0.00929
	(0.186)	(0.195)	(0.230)
Cooling & ventilation eq.	**1.502*****	−0.108	**−1.548*****
	(0.314)	(0.320)	(0.599)
Other general purpose mach.	**0.910*****	**0.473****	**−0.865****
	(0.213)	(0.221)	(0.345)
Agricultural and forest mach.	0.490	−0.636	−0.0575
	(0.305)	(0.405)	(0.400)
Machine-tools	0.00264	**0.852*****	**−0.843****
	(0.200)	(0.209)	(0.331)
Special purpose mach.	0.167	0.257	−0.336
	(0.146)	(0.163)	(0.207)
Electrical apparatus	0.183	**0.772*****	**−0.596****
	(0.182)	(0.192)	(0.275)
Automotive transport eq.	**0.442****	−0.379	−0.155
	(0.201)	(0.260)	(0.269)
Other business services	**0.464****	**0.407***	**−0.658***
	(0.232)	(0.240)	(0.366)
Constant	**-0.357*****	**−1.549*****	**−1.364*****
	(0.0786)	(0.0941)	(0.100)
Observations	3377	3377	3338
Pseudo R^2	0.0514	0.131	0.0357

Standard errors in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

computers or software.

The results also convey that innovations driven by problems and technological opportunities are connected to frequencies of 16-32 years of duration, depicted in Fig. B1. These innovations were clustered some time after the downswing phase of the Kuznets cycle, around 1980 and 1998. Accordingly, the coefficients for the long-run frequency are negative when we specify a lag of 4.[12] This does not suggest a causal relationship from GDP growth to innovation activity, but informs of, if anything, a generic interplay between long-run economic growth and innovation activity, as has been suggested by Schön (2010). In this long-run interpretation of Swedish economic history, new technologies, such as micro-electronics, have been diffused after the economic crises of the 1850s, 1890s, 1930s and 1970s, following a pattern in which a first surge in innovation activity must first be directed towards overcoming obstacles and enabling the commercial exploitation of new technologies. After a first surge in innovation, the technology matures and a wider diffusion is made possible, enacted through a second surge in large scale infrastructural investment, such as the investment in telecommunications that occurred from the mid-1990s.

5. A brief history of creative response

Further insight into the historical patterns of innovation is given by the diverse and historically specific problems and opportunities that can be revealed by a qualitative analysis. This section draws on the collected biographies for the 3377 innovations, to chronicle the main patterns and historical sources of innovation as a creative response in Sweden during 1970–2007. The patterns of creative response observed can, on the basis of innovation biographies, be understood in terms of three broad technology shifts occurring in two surges around the mid-1970s and 1980s and during the 1990s:

- An opportunity-driven expansion based on micro-electronics with emphasis on factory automation during the 1970s and 1980s.
- The environmental, economic and organizational problems that surfaced during the structural crisis of the 1970s.
- An expansion during the 1990s with emphasis on opportunity driven innovation in telecommunication, digital technologies and biotechnology, but which also included problem-driven innovations surrounding ICT and renewable energy technologies.

5.1. Opportunities from microelectronics

The surge during the 1970s and 1980s consisted to a large extent by innovations driven by opportunities stemming from the micro-electronics revolution, e.g. the development of minicomputers, microprocessors, laser technology, computerized numerical control systems and computers. ICT innovations during the 1970s and 1980s were largely focused on industrial applications and *factory automation*. The activity centered around ICT innovations in Sweden during the 1970s and the 1980s has been understood as a technological system, composed by the development of control systems, computer controlled machinery, automation equipment and automatic guided vehicles (Carlsson, 1995; Taalbi, 2017). The diffusion of microprocessor based technology enabled new generations of machinery and instruments for control and measurement with improved performance. At the core of this development lay control systems and computer equipment. Numeric Control (NC) systems had already been introduced into machinery during the course of the 1960s, but predominantly among large firms, e.g. ASEA.[13]

The exploitation of microelectronics in machinery innovation meant a sizeable number of industrial robots developed by Swedish firms and machinery innovations taking advantage of minicomputers, computers

[12] Lag length 4 is chosen since the average development time of innovations is 4.3 years. When using only one lag, no coefficients are significant except the long-run frequency component for problem-driven innovations. The cross-correlation between long-run growth and problem-driven, technological opportunities and market opportunities reach largest modulus for lags of 3, 8 and 4 respectively.

[13] ASEA was one 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).

or image processing equipment. Swedish firms lay at the forefront of the development of robots. ASEA Robotics (ABB Robotics after 1988) was a market leader in this field, launching several notable robot innovations during the period studied.[14] The role played by large firms, such as Asea, Saab-Scania, Electrolux and Volvo, in the ICT sector during its early stages has been highlighted by others (Carlsson, 1995). During the 1980s innovation activity in ICT was however increasingly carried out by smaller and younger firms observing market niches or technological imbalances (see Taalbi, 2017 for further discussion). Several new firms were developing robots and auxiliary parts for robots while some were integrating robots in manufacturing systems. Other small firms were developing computers. Sweden's first personal computer called ABC 80 was launched on the Swedish market in 1978 and had been developed by the three Swedish companies (Luxor Industri AB, Scandic Metric AB and Dataindustrier AB) to meet the difficulties arising from a saturated market in home electronics (TV and audio systems).

In addition, automated guided vehicles (AGV) were an important component of the factory automation technological system during this period. While a hampering factor in the development of AGVs was the limited capabilities and bulkiness of the control systems for the guidance of the vehicles, these problems were being resolved in the advancement of integrated circuits and microelectronics. Accordingly, several control systems were developed to enable AGVs.[15]

5.2. Problem driven search in the 1970s and 1980s

While the surge of the 1970s and 1980s to a sizeable extent resulted from the application of micro-electronics in machinery and the development of computers and electronic equipment, these innovations do not explain all innovation activity during the structural crisis. Rather, various negative inducements for innovation emerged from the end of the 1960s, being accentuated during the structural crisis. As shown in Fig. 7, the increase in problem-solving innovations observed during the 1970s was carried by innovations responding to three types of problems: (a) *environmental problems* from industrial production, e.g. waste and emission, (b) *organizational problems*: techno-economic problems involving the work environment, and (c) *economic*: obstacles to the rational production, transportation or use of goods. This, while a larger share were directed towards solving technological obstacles from the 1990s (see Section 5.3).

The sources of creative response during the structural crisis lay thus both in problems accentuated due to the oil and energy crisis and in waning demand and profitability. Problem-solving innovations were during the 1970s the creative response to several generic problems associated with the energy crisis, the oil crisis, the situation developing from a Swedish shortage of wood, and the increased awareness and political pressure to reduce pollution and industrial waste in the chemical, paper and pulp and the forestry industries. Moreover, several industries faced issues related to the working environment, which motivated technological development during the 1970s, some of which were negative externalities afflicting the working environment (asbesthos and toxic gases) and others e.g. occupational noise and work related injuries.

5.2.1. Renewable energy technologies

The creative response to environmental problems culminated during the crisis of the 1970s. This can in part be explained by an increased social and political awareness of environmental issues that emerged in the 1960s. The Swedish Environmental Protection Agency (Naturvårdsverket) was formed in 1967 and Sweden's first environmental protection law, the Environmental Protection Act was introduced in 1969.[16] While some environmental development projects were started during the 1960s, the energy and oil crisis of the 1970s intensified or spurred the search for new energy sources as well as alternative fuels and other attempts to reduce oil dependency. The energy use of the Swedish industry shifted during the 1970s and 1980s from oil to electricity, district heating and biofuels. Biofuels have from the 1990s become increasingly important (Kander, 2002). A large number of innovations were explicitly developed in response to these challenges: heating pumps for district heating and various new technologies for the use of methanol for engines, coal, peat and biofuels such as wood, forest and pulp residue.

Heating pumps were developed and diffused rapidly after the structural crisis of the 1970s, which has been attributed to the fact that the oil crisis and the increased energy prices made heating pumps an economically feasible alternative and the incentives to reduce oil dependency (Kaijser et al., 1988, pp. 76–92). The heating pump technology reinforced and enabled established energy distribution systems, electric heating and district heating, to be developed further. There were however techno-economic obstacles to be overcome. Attempts to construct an economical standard device had failed due to technical construction problems (*Ny Teknik* 1972:14, p. 16). Moreover, most heating pumps tested in Sweden had not worked in low temperatures, which was a bottleneck tackled by several firms. Innovations surrounding the production of power using biomass are observable from the early 1980s. Several innovations were during this time developed aiming to overcome techno-economic obstacles to the use of various forms of bio-energy, e.g. from forest residue, peat and recycled biological waste. Among these, wood and forest residue was one of the main alternative fuels. An urge to make better use of wood material was driven by a wood shortage during the 1970s, but also the growing demand for chips for energy production. This led to the development of methods that attempted to make profitable the processing of forest residue. Other examples were firms that developed bio-energy production systems and agriforestry for the production of biomass. Swedish firmswere also pioneers in developing technology for the use of gasified biomass (Johnson and Jacobsson, 2001).[17]

5.2.2. Problems in the automotive industry

The attainment of improved emission control and reduced exhausts has required the interplay between car and truck producers and producers of catalytic converters, drive and control systems and motor engines. Awareness of the harmful effects of air pollution spurred new legislation and research to reduce pollution in the 1960s (Elsässer, 1995; Bauner, 2007). The US was in many aspects a precursor in the sharpening of vehicle exhaust legislation and Swedish legislation often followed its example. Saab-Scania and Volvo were two early Swedish contributors. They developed independently three-way catalytic converters (TWC), introduced in new car models for the US market in 1976

[14] Several notable innovations were developed by ASEA. ASEA's IRB 6 launched in 1973, was the first wholly electrical micro-processor controlled robot commercially available (Glete, 1983, *Modern Elektronik* 1986:16, pp. 47–49). ASEA began research and development in 1977 of a new robot system based on computer based image processing technology. The result, “ASEA Robot Vision”, was commercialized in 1983 (*Ny Teknik* 1983:37, p. 3; *Verkstäderna* 1983:13, pp. 44–46).

[15] The Swedish firm, Netzler and Dahlgren (NDC) emerged as one of the pioneers in the development of AGV control systems when it became involved in a Volvo project, which was the first installation of AGVs in Sweden. In 1972 NDC developed the control system for Volvo's carriers (*Ny Teknik* 1976:38, pp. 4–5). As a result of the project Volvo developed and commercialized its carrier technology, for instance at Tetra Pak. NDC was also involved in developing the computerized control system in this project. A subsidiary to Volvo, ACS (AutoCarrier System) was formed in 1976, based on a guided carrier, the so-called Tetracarrier (Elsässer, 1995, p. 167, *Automation* 1978:7, pp. 32–34; *Verkstäderna* 1977:13, pp. 43–5).

[16] The environmental policy aimed to establish consensual agreements with each production unit based on what was technically and economically feasible, and environmentally desirable. Emission standards were negotiated at the industry-level.

[17] For example, in the mid-1980's SKF Steel had developed its gasification process Plasmadust (*VVS & Energi* 1983:2, pp. 83–84; *Jernkontorets Annaler* 1983:2, pp. 22–23; *Kemisk Tidskrift* 1983:2, p. 17) which enabled the use of coal based fuels, e.g. peat, and biomass in energy production.

(Elsässer, 1995; Bauner, 2007, pp. 254–255; *Verkstäderna* 1988:12, pp. 93–94).

The introduction of TWC in Europe however faced hurdles to be overcome. In particular, the introduction of TWC required the availability of unleaded fuel, as lead contaminates and prevents catalysts from treating the exhaust. This process was slow in Europe. In Sweden, unleaded fuel gradually became available from 1986. In 1986 the Vehicle Exhausts Act was passed by the Swedish parliament, which meant the introduction of requirements for emission control for new cars (*Kemisk Tidskrift* 1985:13, pp. 10–14; 1987:10, pp. 48–49). By then, TWC equipped vehicles were available on the Swedish market, and TWC was made mandatory in 1989 (Bauner, 2007, pp. 257–258). As a response, Saab-Scania launched an improved emission control technology in 1988 based on TWC and unleaded fuel, adapted for the Swedish climate and driving conditions. The system was introduced on all car models with 16-valve engines (*Verkstäderna* 1988:12, pp. 93–94). An injection engine constructed for unleaded fuels and catalytic emission control was launched in 1989 (*Verkstäderna* 1989:12, p. 66).

A set of stronger incentives to eliminate obstacles to the diffusion or exploitation of a new technology, have also characterized the development of electric and hybrid automotive vehicles. The increased oil, fuel and energy prices in the 1970s forced the automotive industry to concentrate efforts in this direction. Costumer-demand, environmental awareness and sharpened legislation has since then also driven technological development in this direction (Elsässer, 1995). The development of hybrid and electric cars have prompted other complementary innovations. The difficulties in developing sufficiently light and energy-dense batteries with sufficient life length have been salient critical problems that have hampered the commercialization of electric and hybrid cars for decades. Early electric cars and batteries were developed during the 1970s, for use in postal services.[18] The renewed interest in electric cars sparked several development projects of new batteries and electric cars, all of which were targeting the core techno-economic obstacle of limited life lengths and limited driving range. Towards the beginning of the 1990s, there were several public and private actors promoting the development of electric cars (Fogelberg, 2000, p. 116).[19]

5.2.3. Problems in the forestry sector

The forestry sector emerges as one of the most prominent examples of a set of closely interrelated social, technical and economic problems that spurred innovation activity. In 1974, an acute shortage of wood emerged as a result of that the deforestation level had reached the maximum level allowed by Swedish legislation (Josefsson 1985, p. 241). As a result, firms developed mechanization techniques, whole tree deforestation methods and new machinery to enable increased wood volume per tree felled. In addition to the wood shortage, there emerged other incentives to the mechanization of forest cultivation, felling and culling: high labor costs, labor shortage due to far-gone urbanization and the need for forest regeneration to reassure the supply of raw material for pulp, paper and wood processing industries. Accordingly, there were numerous innovations developed to introduce new methods, machinery and tools to achieve a mechanization of forestry activities for one or several of the reasons described. Many of the innovations had to eliminate technical obstacles to mechanization.[20] Generic unprofitability was very frequently such an obstacle, becoming the core problem to overcome for several innovations.[21]

The shortage of wood also affected sectors downstream. Both the wood processing industries and the pulp and paper industries were affected, while simultaneously struggling with higher energy costs and a felt pressure to transform to environment friendly production methods. Thus one may observe machinery, electronic and other innovations that were attempts to economize on the raw materials, and some firms launching methods and machinery to produce wood and wood products out of waste materials.[22]

5.2.4. The work environment

Problems pertaining to the work environment induced innovations, especially in the engineering, construction and mining industries. The 1970s has been characterized as a period of great change in work environment policy and as a period as for work environment improvements were met by employers (see e.g., Thörnqvist, 2005). During the post-war period, work environment measures were regulated in centralised agreements between the labor unions and employers organisations. Focus was placed on reducing work place accidents, while other problems, for instance occupational diseases were not given the same amount of attention. However, a broader political awareness of these issues was stirred in the early 1970s that led eventually to The Work Environment Act, passed by the Swedish parliament in 1977.

This development was also related to social conflict. The end of the 1960s and the 1970s saw a rise in social conflicts and labor militancy that added urgency to political and organizational responses. Social conflicts were for the most part concentrated to ”old” industries of Fordist mass production. An important event was the miners' strike 1969–1970, triggered by discontent with piece wages and in part a reaction to the advert working environment problems that resulted from increased mechanisation carried out by iron ore company LKAB during the 1960s. The major environmental problems were work place accidents, diesel exhaust and poor ventilation capacity, but also vibrations from drilling machines and occupational noise. While the main short term measures taken by LKAB were to search for new labor-saving methods to enable increased mechanisation, other firms developed innovations aimed to appease the work environment in the mining sector.[23] LKAB launched the “Kiruna bolt” in 1970 (*Ny Teknik* 1970:20,

[18] One such example is the well-known electric car “Tjorven” produced by Kalmar Verkstad AB in 1969–1970 and used in the Swedish postal services. In the end of the 1970s, Saab-Scania, AGA Innovation AB and the Swedish Post Office developed an electric car with improved battery capacity and driving range (*Verkstäderna* 1977:4, p. 34; 1977:12, p. 39). State-owned SUAB developed a nickel-iron battery for electric cars with increased energy density to enable increased driving range (*Transport Teknik* 1979:10, p. 312). The battery was used in the development of an electric car for the Swedish telecommunications authority, Televerket (*Transport Teknik* 1979:10, p. 312).

[19] For instance, a project to develop electric cars was initiated, involving Gothenburg Municipality, Vattenfall and ABB, who had developed a sodium–sulphur battery. ABB's sodium–sulphur battery was given much attention as it was thought that it could mean a breakthrough for the electric car. It had an energy-density four times higher than the best lead batteries and enabled increased driving range (Ny Teknik 1988:32, p. 5; *Verkstäderna* 1990:10, pp. 75–76; 1992:6–7, pp. 56–58; *Teknik i Transport* 1990:7, p. 36; 1990:7, p. 41). The Institute for Microelectronics (Institutet för Mikroelektronik) was also developing a new battery, using the iron oxidation to enable increased driving range and, in particular, less heavy batteries. Apart from insufficient life length the innovation aimed to overcome the problem of weight and bulkiness in earlier batteries (*Kemisk Tidskrift* 1989:4, pp. 46–47).

[20] For instance, one of the reasons why the mechanization of tree felling was lagging behind was the lack of felling tools that could compete with manual labour. Such a tool was therefore developed by a pioneer in forestry mechanization, Östbergs Fabriks AB (ÖSA), and the Swedish Forestry Research Institute (*Sågverken* 1977:2, pp. 97–101, p. 125).

[21] When launching a new forest machine labelled “Kockums 81-11”, Kockums claimed “to have the solution to one of the biggest problems of forestry – to attain profitability in early weeding” (translated from *Svensk Trävaru- och Pappersmassetidning* 1982:11, p. 729). At the time most of all culling was carried out with chain saws. This was considered costly, cumbersome and unprofitable. The machine was therefore adapted to become small and flexible (*Svensk Trävaru- och Pappersmassetidning* 1982:11, p. 729; *Sågverken* 1982:10, pp. 59–61).

[22] For instance, machinery to produce chip wood by stumps and waste wood was launched in 1975 by a firm in northern Sweden (*Sågverken* 1975–11, p. 839). Another example is a method to produce planks and boards from fiber material from garbage. According to the responsible for the development ”[n]ow... sawmill owners do not need to complain about the shortage of raw materials any longer” (*Sågverken* 1977:10, p. 905).

[23] Some were launched shortly after the strike. Atlas Copco, a major supplier of rock drilling equipment, for instance developed a dust collector to decrease the problems with dusting in rock drilling (*Bergsmannen med moderna material SJM-bulletin* 1972:6, p. 149). Saab-Scania's first automatically controlled unmanned vehicle was developed as a mining truck due to the apparent need to improve the working environment (*Transport Teknik* 1971:6, pp. 280–1).

p. 10), a rock bolt developed to solve the problems with collapse risks and work-related injuries in mining operations. Over the following years, LKAB, other mining companies and subcontractors continued to make several similar innovations, as the use of large scale mining methods had led to increasing problems with failing rock strength (*Ny Teknik* 1981:5, pp. 12–13).[24]

The engineering and construction industries experienced different kinds of working environment problems. Attention was paid to problems with occupational noise and injuries from vibrations in drilling operations, which led to the development of machinery and equipment designed to reduce vibrations in a wide range of applications. The engineering industry also had problems involving toxic welding gases, which led to the development of new equipment and facilities for flue gas purification. Development efforts were also made in order to deal with the adverse health effects of organic solvents in the plastic, graphic and chemical industries. National working life institutes were established to develop improvements to the problem with organic solvents. Styrene, a hazardous chemical, was a problem in particular for the plastic industry, which motivated several innovations during the 1970s and 1980s.

A last case was the removal of asbestos from construction activities and facilities. During the latter part of the 1960s studies had shown that the risk for pleural cancer was higher for asbestos patients and workers exposed to asbestos. Alarms about cases of mesoteliom among workers exposed to asbestos led to sharpened regulations, that were introduced in 1975 (Thörnqvist, 2005, p. 282). Asbestos was totally prohibited in 1982. In this process innovations were introduced to either replace asbestos, or associated machinery or methods. While asbestos had not been banned, the Swedish National Board of Occupational Safety and Health (Arbetarskyddsstyrelsen) prohibited the use of high speed machinery due the amount of asbestos emissions from 1977. The process of dealing with and removing asbestos was regulated from January 1979. In consequence, several innovations were developed to deal with problems emerging in the removing and replacement of asbestos.[25]

5.3. Opportunities and problems in a second surge

Behind the surge in innovation activity after the crisis of the 1990s lay a continued diffusion of micro-electronics and a vigorous development of telecommunication and digital technologies. During the 1980s and 1990s the technological and market opportunities created by the introduction of digital systems, mobile telephony services and Internet were becoming ample. As in the US, Japan and UK, the expansion of telecommunication technologies in Sweden was preceded by market deregulations in the mid-1980s (Fransman, 2001, 2002). The monopoly was completely abolished with the Telecommunications Act of 1993.

These deregulations were followed by a wave of product development and entrant firms in the field of telecommunications. The count of mobile telephone and consumer electronics innovations increased after the crisis of the 1990s and culminated in 1999–2000. L M Ericsson, the major player in Swedish telecommunications, accounted for a large part of these innovations. Ericsson for instance developed the first wap phone (2000), the first Bluetooth product (though the Bluetooth technology was developed by a consortium of mobile telephony actors) and the first mobile telephone supporting both Bluetooth and MMS (Multimedia Messaging Service). The bulk of other consumer electronics innovations were developed by new entrant firms exploiting market or technological opportunities.[26]

The first Swedish network was connected to the Internet in 1984, but it did not become publicly available in Sweden until 1994, when a startup firm, Algonet, connected Internet with the Swedish telephone network and provided Internet access. The ensuing deployment of Internet and telecommunication networks spurred opportunities for investment and innovation in data communication equipment, transmission systems and network components. But new opportunities were not the only driving forces in this surge of ICT innovations; imbalances and technological bottlenecks, have been driving development of these innovations to a considerable extent. In particular, these types of innovations have played a large role in the deployment of Internet infrastructure. The development of ADSL technology (Asymmetric Digital Subscriber Line) was commenced internationally to address a capacity bottleneck (Fransman, 2001, pp. 125–126). Similarly, when Telia was the first in the world to transmit high resolution TV images using the later transmission technology VDSL (Very high speed Digital Subscriber Line) it was noted that modems and network components were necessary for a commercially functioning technology (*Ny Teknik* 1997:15, p. 4). In 1999, Telia Research could launch a series of chips adapted for VDSL, developed together with the French chip manufacturer ST Microelectronics (*Ny Teknik* 1999:45, p. 11). Innovations included not only mobile telephones, but data communication equipment (e.g. modems), network switches, optic fibers, installation tools for fiber cables, mobile positioning systems and radio systems. Almost without exception, the innovations launched by these firms were directed towards solving critical problems in the expansion of networks.[27]

A last source of innovation in ICT has been various security problems that early on followed the introduction of industry and personal computers and data communication systems. Already in the 1980s there were Swedish innovations aimed to prevent database hacking, or computer thefts.[28] As more people began using the Internet, and as more transactions were carried out over the Internet several firms also

[24] For instance, in April 1975, there was a rock movement in LKAB's Kiruna mine that necessitated a new method to reinforce rock excavations (*Ny Teknik* 1978:12, pp. 16–17). Boliden, another mining company, had experienced increased problems with misfired rounds and accidents in rock blasting and contracted an electronics firm (Tri Electronics) to solve the problem. This resulted in the development of a new ignition system for rock blasting (*Ny Teknik* 1975:20, p. 13). Another firm developed a device that allowed the mechanization of the charching of explosives to avoid the previously large risk of rock collapse and heavy manual work (*Ny Teknik* 1977–35, p. 30).

[25] One firm had for instance developed a mechanical method for cutting and turning of asbestos pipes that was claimed to substantially reduce dusting (*Ny Teknik* 1976:30, p. 26). A special system with equipment was developed during two years by a working group involving the construction workers, the trade inspection (Yrkesinspektionen), the National Board of Occupational Safety and Health and three manufacturing firms to solve the problems (*Verkstäderna* 1979:6, p. 18).

[26] For instance, Array Printers, started in 1987 to develop and commercialize a printing technology, Toner Jet, invented by the founder Ove Larsson. Array Printers launched two innovations (a new fax machine 1994 and four colour printer 1995). Another successful example is Axis Communications, started in 1984 to develop and sell printer interfaces. In 1995 Axis launched the world's first centralized IP camera "Neteye" (*Elektroniktidningen* 1996:15, p. 8; *Ny Teknik* 1996:38, p. 18). Another entrant firm developing consumer electronics was Anoto, started in 1996 as C Technologies by Christer Fåhraéus. Anoto's core innovations were C Pen, a pen that transmits text to mobile phones via Bluetooth (*Ny Teknik* 2000:16, p. 28; 2000:46, p. 35; 2003:12 Part 2, p. 1; *Elektroniktidningen* 2002:7, p. 15; *Telekom Idag* 2001:8, p. 15; *Automation* 2002:5, pp. 24–26), and an image processing circuit invented by Fåhraéus that lay at the core of the camera technology of the scanning pen (*Ny Teknik* 2002:15 Part 2, pp. 10–1; 2002:43 Part 2, p. 15; 2002:25–33 Part 2, pp. 8–9; 2003:5 Part 2, p. 10).

[27] For instance, Netcore (later renamed Switchcore) launched a circuit that could handle both ATM and IP technology. The technology came from a research project in which Ericsson Components, Saab Dynamics, the Royal Institute of Technology and the Universities of Linköping and Lund participated (*Elektroniktidningen* 1997:19, p 4 *Ny Teknik* 1998:25–32, pp. 16–17). The circuit was customized for IP switches and routers for the Gigabit Ethernet standard. With increased traffic, the data switch became a bottleneck, but with Netcore's circuit it became possible to build faster and cheaper switches. Other examples were the innovations of Dynarc and its sister company NetInsight, stemmed from the research group at the Royal Institute of Technology that since the 1990 developed DTM (Dynamic Sychronous Transfer Mode), a network protocol enabling high speed data switching and increased capacity in IP networks. Net Insight launched a network technology able to provide speeds of several terabits per second. (*Ny Teknik* 1998:25–32, pp. 16–17) Dynarc developed a PBX for IP networks based on DTM commercialized in 1998 (*Telekom idag* 1998:8, p. 11; *Ny Teknik* 1998:25/32, pp. 16–17).

[28] For instance, Concentus, an electronics company formed in Norrbotten, developed a Swedish modem with filter for hackers, launched in 1985 (*Ny Teknik* 1985:47, p. 47). Nordnet and Alfanet launched two data security systems in 1988 aimed to protect against hacking (*Ny Teknik* 1988:9, p. 28).

emerged in the late 1990s that were attempting to eliminate obstacles to secure online transactions.

5.3.1. Renewable energy technologies from the 1990s

While the bulk of innovations driven by environmental problems were concentrated to the first half of the period, it is worthwhile to stress that the latter half of the period saw an increasing number of innovations aimed to solve environmental problems, or to solve obstacles to the introduction of new renewable energy technologies.

Many of these innovations were developed in the fields of renewable material and energy technology and emission control technology. Some firms were developing innovations to solve obstacles to the wider use of solar energy. Albeit struggling with a lack of resources, a handful of firms developed wind power technologies and wind turbines from the 1990s and on.[29] Innovations for the production of biofuel were numerous, expanding on previous advances.[30] The period also saw further innovation in emission control technology, or automotive vehicles or motors exploiting emission control technology, as well as hybrid electric vehicles. Several innovations were launched by the large automotive and truck manufacturers (Volvo, Saab and Scania). Others were developed by new firms.[31] Other clean technology innovations were renewable materials or products aimed to replace the use of hazardous chemicals, often driven to respond to new environmental regulations.[32]

6. Conclusions

Jacob Schmookler once described technological change as the "terra incognita" of economic theory. While our understanding of the determinants and driving forces of innovation has greatly improved since, the empirical and theoretical literature conveys varying and sometimes conflicting messages on what incentives or conditions are conducive to innovation. This study is an attempt to give a comprehensive and systematic study of what drivers actually have mattered in the Swedish innovation system. To this end it suggests a theoretical framework that combines the notion of innovation as search for new combinations (Levinthal, 1997; Frenken, 2000, 2006; Arthur, 2009), with the notion of innovation as a creative response to discrete events (Schumpeter, 1947; Antonelli, 2011, 2015). The resulting framework separates out four different factors behind innovation: problem-driven, opportunity-driven (market or technological opportunities) and institutionalized search.

The results of applying this analytical framework to Sweden, 1970–2007, suggest that innovation activity was not the mere result of institutionalized search for improvement along well-known trajectories. Rather, most innovations launched during the period were developed as a creative response to problems and imbalances emerging in the process of economic development or spurred by the observation of new technological opportunities. Accordingly, the notion that economic, social and other problems serve as central focusing devices is by no means exaggerated. Environmental, economic and organizational problems that emerge in specific historical situations have shifted the focus of firms towards search for new solutions. Similarly, new technologies, in particular those provided by the diffusion of general purpose technologies such as micro-electronics, have opened up new opportunities and have been a salient feature in the pattern of Swedish innovation activity.

The basic corollaries of this study are therefore unambiguous and simple: non-incremental innovation appears to be motivated by the *discrete*, rather than continuous, incentives provided by history-specific problems on the one hand – the economic and environmental problems and the problem complexes induced by institutional change and legislation, social issues and technological imbalances – and on the other the vast opportunities provided in the diffusion of general-purpose engines and new scientific knowledge.

These results can be juxtaposed to the historical debates on major technology shifts, alluded to in the introduction of this study. Macro-inventions, such as the steam engine, electric motor and micro-processor, have sometimes been considered much less influenced by economic selection mechanisms, as per (Mokyr, 1990, p. 13) they are "inventions in which a radical new idea, without clear precedent emerges more or less ab nihilo" and they "do not seem to obey obvious laws, do not necessarily respond to incentives, and defy most attempts to relate them to exogenous economic variables". Allen (2009) by contrast sees macro-inventions as susceptible to relative factor price inducement, since the development of a macro-invention is time-consuming and expensive (Allen, 2009, p. 141). This study neither deals with 18th century Britain, nor with innovations of quite the same stature as, e.g., Newcomen's steam engine of 1712. However, our study lends support to the view that also the more radical innovations are greatly influenced by discrete problems and opportunities, in fact much more often than not. In other words, the set of incentives, the signals of problems and opportunities, that a society presents its inventors are likely to determine its ability to bring forth radical innovation. The statistical and historical analyses also suggest a more complicated relationship between innovation patterns and economic growth than the simple positive or negative relation to business cycles that has sometimes been suggested.

Rather, our results stress that innovation can be understood in terms of the long-term interplay with economic mechanisms, fuelled by growth prospects, but also as a response to policy change, economic crisis and social upheaval. On the one hand, problem-solving innovations were intimately connected with environmental, economic and social problems that affected the oil-based, automotive and consumer durable sectors in the 1970s and 1980s. A significant role was also played by the 1970's energy crisis in intensifying the search for energy saving products, alternative fuels and attempts to reduce oil-dependency. However, no small part of the creative response to environmental problems is attributable to the environmental legislation (1969) and energy policies introduced during the 1970s. Environmental policy, regulation and e.g. emission standards have since been an important driver of innovation in the pulp and paper and automotive industries. In more recent years, renewed interest in renewal energy technology, has followed from technological breakthroughs and the overcoming of critical imbalances.

On the other hand, the numerous opportunity-driven innovations

[29] One development project was aimed to construct a wind turbine for use in midland areas and adapted for unfavorable wind conditions (*Verkstäderna* 2002:10, pp. 18–19). Another firm responded to the high costs of wind power and developed an electricity generator for wind turbines (*Ny Teknik* 2004:39, p. 5; 2007:7, p. 28; 2007:39, pp. 8–9). In one article the problem was described: "Wind power is expensive today. Therefore, gear switches that change up the rotor blade speed of most wind turbines are not popular among the power companies. They are a common cause of costly breakdowns. A less common alternative is to use direct-driven generators without gearbox. The catch is that they are heavy and therefore expensive" (*Ny Teknik* 2007:7, p. 28; translation by the author).

[30] The Chemrec process (developed by a firm with the same name) was aimed to replace the recovery boilers and enable increased energy efficiency (*Ny Teknik* 1990:16, p. 5; *Svensk Papperstidning* 1991:10, pp. 32–33; 35–36; 39–40; 1994:7, p. 50; 2001:7, p. 24; 2001:7, pp. 48–50; *Kemisk Tidskrift* 1990:5, pp. 20–21). The result of seven years of research, LignoBoost AB developed a method to extract high grade biofuel from black liquor. While enabling purer black liquor, the process was primarily motivated to improve profitability and overcome the bottleneck of the costly recovery boilers (*Svensk Papperstidning* 2006:7, pp. 14–16; 2007:2, p. 46; *Ny Teknik* 2006:23, p. 6). Other examples are Termiska Processer i Studsvik (TPS), developing a gasification technology for biofuels (*Ny Teknik* 1995:36, pp. 24–25; *Ny Teknik* 1998:24, p. 10) and Ageratec, which developed a small scale facility for the production of biofuel from oil or fats (*Ny Teknik* 2006:45, pp. 26–7).

[31] Notable examples are an exhaust emission control developed by Emission Technology Group (*Transport idag* 2004:11, p. 7) and an innovation, developed by Varivent and commercialized by Haldex, to solve the problem of energy losses in EGR technologies (*Kemivärlden* 2003:8, p. 16; *Ny Teknik* 2003:1–3, p. 12; 2006:10, p. 4).

[32] PP Polymer developed several such innovations, among those an environmentally friendly glue (*Ny Teknik* 1996:34, p. 22) and a flame retardant aimed to replace the use of hazardous halogens (*Kemivärlden* 2004:3, p. 5; *Kemivärlden Biotech med Kemisk Tidskrift* 2006:6, p. 8).

were fundamentally linked to micro-electronics, ICT and biotechnology. Also these technologies have evolved in a pattern of two surges, one following the structural crisis of the 1970s, and one during the IT boom of the 1990s. These surges obtained momentum following upon technological breakthroughs and the coming into place of institutional changes, e.g., the deregulation of the telecommunications monopoly, which enabled vigorous entry of new innovating firms. In brief, both the cases of ICT and renewable energy technologies emphasize creative response in hard times and the long time lapses present in the exploitation of GPTs and solution of critical problems, but also the crucial role of innovation and environmental policy.

In the introduction of this paper, we alluded to the prospects of "a general theory of innovation". It is obvious from the basic results of this study that innovation must be understood in its proper historical setting, which naturally flies in the face of such sweeping theorizing. In short, history matters. Nevertheless, the results point to some lessons of importance for a wider array of cases and historical debates, as well as for policy.

First of all, it appears that there are distinct industrial patterns of creative response. Problemistic search has been an especially salient strategy in medium-high technology industries, such as machinery and electrical apparatus, automotive, chemicals and plastics. Technological opportunities, on the other hand, have dominated in high-tech industries, mainly ICT and pharmaceuticals, but also in automation machinery equipment. These two search strategies are also associated with higher market and firm novelty of the innovations, indicating a possible conjunction with explorative search strategies and disruptive innovation processes. These results need further qualification (see chapter 5 in Taalbi, 2014), but they suggest to consider the broader notion of creative response as a central dimension of sectoral systems of innovation and technological regimes, which have hitherto mainly been discussed in terms of market structure, opportunity and appropriability conditions (Pavitt, 1984; Malerba, 2002).

Second, a corollary of the theoretical framework is that the creative response to discrete events emerges precisely from situations of high complexity and uncertainty. The empirical findings may be taken to support that there is an important and fundamental connection between complexity and search strategies. Understanding how the complexity of technological systems change search strategies and avenues for innovation is key for innovation policy, especially if there is increasing complexity in research and technological systems (Strumsky et al., 2010; Youn et al., 2015). Our results would tentatively suggest greater emphasis on supporting innovational interdependencies, opportunities or problem-solving innovation in response to increased innovational complexity (compare Markard and Hoffmann, 2016). This is however a connection that requires further theoretical and empirical analysis.

The limitations of the current theoretical framework lie in part in some of the innate assumptions of the NK-model. As it stands, the model is static and does not accommodate evolving interdependencies or changing degrees of NK-complexity (Frenken, 2006). A second limitation of the present analysis, is of course that what drives innovation is a different issue entirely from what factors determines the dynamic capabilities of firms and the economic of or the innovative potential of economies. Put otherwise, continued research along these lines should inquire into what capabilities of firms or characteristics of innovation systems are conducive to creative response and how interdependencies between innovations, firms and institutions matter when faced with ever greater complexity.

Appendix A. Technological distance

An intuition derived from historical observation and the *NK* model framework is that technological distance is higher to those combinations that have higher payoffs.

Consider the fitness equation:

$$z = \frac{1}{N}\sum w_i(s_i; s_{i_1}, \ldots, s_{i_K}) \tag{A.1}$$

We are not interested in comparing across different values of N, wherefore we can omit the scale factor $\frac{1}{N}$. To derive the average search distance to some characteristic, we wish to derive the probability that a characteristic is at least α, upon changing d input modules.

Changing one input module will, through K epistatic relations, affect a certain number of other modules. The probability that one certain module will be affected by changing d modules is

$$p = 1 - \left(1 - \frac{K}{N-1}\right)^d \tag{A.2}$$

and in general, the probability that, in addition to the d modules modified, in effect j of the fitness contributions w_i are affected is

$$\mathscr{P}(j) = \frac{(N-d)!}{j!(N-d-j)!}p^j(1-p)^{N-d-j} \tag{A.3}$$

Now, since characteristics is a sum of N random elements, the distribution of characteristics is described by an Irwin-Hall distribution $\mathscr{I}(N, z)$. Importantly, the change in z brought about by a change in X of the fitness contributions w_i is described by a zero mean Irwin-Hall distribution $\mathscr{I}_0(2X, z)$.

Let the total number of fitness contributions changed upon modifying d input modules, be $X = d + j$. The cumulative density function describes the probability that z is less than or equal to α and is given by

$$\mathscr{C}\left(X, \alpha\right) = \frac{1}{2X!}\sum_{k=0}^{\lfloor \alpha \rfloor}(-1)^k\binom{2X}{k}(\alpha-k)^{2X} \tag{A.4}$$

Given a number of input modules that are modified d we can obtain a function describing the probability of $z \le \alpha$ by combining the probability that in fact $X = j + d$ fitness contributions are changed and the cumulative Irwin-Hall probability density function. This is described by the cumulative probability density function $\mathscr{M}(\alpha, d)$:

$$\mathscr{M}(\alpha, d) = \sum_{j=0}^{N-d}\mathscr{C}(j + d, \alpha)\mathscr{P}(j) \tag{A.5}$$

From this equation we can derive the average distance for a randomly generated NK-model. The probability that there is a combination for which $z > \alpha$ upon changing one module is $\rho(1) = 1 - \mathscr{M}(\alpha, 1)$. The probability that there is a $z > \alpha$ within k steps is given by

$$\rho(k) = [1 - \rho(k-1)][1 - \mathscr{M}(\alpha, k)] \tag{A.6}$$

Accordingly, the expected distance is

$$E(d) = \sum_{k}^{N} \rho(k)k \tag{A.7}$$

The results from these calculations for $N = 10$ are shown in Fig. 4. Observe that it shows the average distance for characteristics that are *higher* than the original characteristics. Expected technological distance is positive in characteristics distance until it reaches the maximum possible (N-1). Technological distance increases to the maximum possible distance at a rate depending on K-complexity. Beyond the maximum, technological distance is independent of distance in characteristics. This level is reached faster for smooth landscapes. This means that there is a relative advantage in employing large search distance in low complexity landscapes, while optimal search distance in rugged landscapes is comparatively low (compare Kauffman et al., 2000). All else equal, this would imply an advantage for incremental innovation strategies in complex systems. The tenet of this study is however that this uncertainty rather induces the employment of heuristics and focusing devices.

Appendix B. Wavelet decomposition of GDP growth

As opposed to traditional Fourier analysis, which are local only in frequency, but not in time, wavelets are local in both frequency and in time. Fourier transform also assumes that time series repeat themselves deterministically. By contrast, wavelet transforms allow for time series whose underlying process may change over time and has therefore considerable advantages in the context of detecting cycles in economic data.

A wavelet transform can be used to decompose a time series into a number $J + 1$ of components

$$y_t = D_{1t} + D_{2t} + \cdots + D_{Jt} + S_t \tag{B.1}$$

where D_j for $j \in \{1, 2, ..., J\}$ are details and S is a smooth trend. Each component D_{jt} of a time series y_t has frequency bands $\frac{1}{2^{j+1}}$ to $\frac{1}{2^j}$ i.e. cycles with length 2^j to 2^{j+1}. The first detail thus has length 2–4, the second 4–8, and so forth.

The present analysis employs the maximum overlap discrete wavelet transform (MODWT) using the Daubechies wavelet basis function and $J = 4$. These are shown in Fig. B1, where short-run has been defined as cycles of 2–8 years, the medium-run 8–16 and long-run 16–32 years. These cycles have the same periodicity as Kitchin cycles, Juglar cycles and Kuznets cycles respectively. A detailed discussion of wavelet analysis and the empirical evidence on economic cycles in Sweden, US and Australia is given in Andersson (2016).

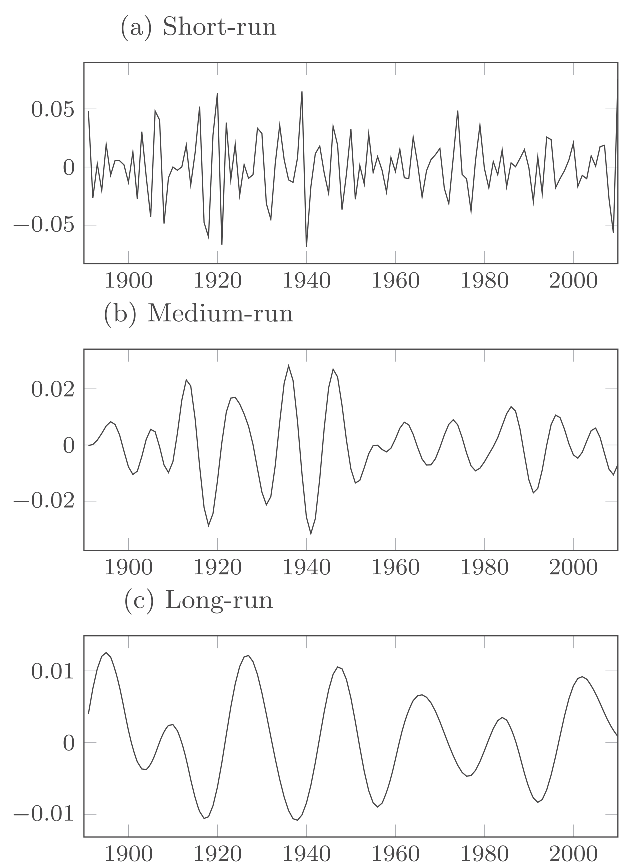

Fig. B1. Wavelet decomposition of GDP growth, 1891–2010.

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