Development of Innovation Monitoring and Innovation Indicators in the Past 50 Years

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Abstract Innovation indicators are instruments to systematically analyse the performance of innovation processes and systems. In this chapter we discuss the evolution of innovation indicators alongside conceptual developments as well as technical and methodological progress. We identify four driving factors, namely (1) new theories/concepts, (2) lower technical thresholds for data analyses and availability of new data, (3) increasing policy demands and (4) technological and economic developments. Our discussion shows that at different stages of the indicator development different factors were the driving forces. The early innovation indicators were mainly R&D-centred with a strong focus on the manufacturing industry and R&D processes in companies as well as the science systems. The innovation system's perspective widened the focus and introduced additional indicators, among them indicators on transfer and collaboration. Data availability and better options for data treatment and analysis gave another push. More recently, information and computer science methods have entered the innovation indicators scene and widened the scope even further. We conclude that indicators are a means to measure and assess constructs which are otherwise not directly measurable. They should not become a means in itself.

1 Introduction

This chapter intends to provide an overview of innovation indicator developments since the early 1970s and against that background to critically discuss current trends and potential future developments. When writing on innovation—and this is essentially the case when writing on innovation indicators—it is always a good idea to start with Schumpeter (1997 [1911, 1934]) and his seminal work on the economic

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development. We will come back to his work when defining innovation. However, our journey of the history of innovation indicators and development over time starts after the Second World War when the new discipline of innovation research started off with conceptual and also empirical analysis of the subject in new research units and institutes, among them Fraunhofer ISI, founded in 1972.

Vannevar Bush published his “Science—The Endless Frontier” (Bush 1945) in 1945 that led to the establishment of the National Science Foundation in 1950 where he essentially suggested the linear model that reaches from basic research to innovation (Godin 2006). In the USA a systematic analysis of innovation processes, their management, as well as conceptual considerations on their formation and effects, in particular by economists and sociologists started as early as the 1930s and 1940s (see, for example, Fagerberg et al. 2011; Godin 2006). A regular report by the NSF was first published in the late 1950s (Godin 2003). At the same time Europe—during this period the USA and Europe mainly represented the industrialised world—was lagging behind. Also systematic data collections of innovation processes or outcomes slowly began to emerge on both sides of the Atlantic in the 1950s and 1960s.

Starting in the mid-1960s, the OECD assumed a very important and impactful standard setting role. It thereby changed the development not only of innovation analysis, but even more so the development of innovation indicators that were needed for these analyses (Godin 2003). It was also decisive for the development and diffusion of science and innovation policies on a global scale (Henriques and Larédo 2013). The OECD was following what we call “the R&D paradigm”—focusing on innovation activities in the R&D departments of companies, mainly in large multinational enterprises. In consequence, indicators were developed and employed that allowed a thorough analysis of R&D inputs and outputs in industry. With the availability of large data sources—not called Big Data in the early years—and the capacities to process them in the first decade of the new century, an emancipation from the R&D paradigm resulted in a new paradigm of innovation research (Sundbo 1997, 2001). This accelerated and shifted the focus to the service sector and also to further aspects of the innovation process.

In the following, we will discuss the evolution of innovation indicators in the last 50 years. We will do so in a contextual and conceptual approach. We analyse the development of the generation and use of indicators in the context of the changes in the conceptual understanding of the innovation process. In addition we look at the changes in the political demand to understand innovation dynamics over time. The chapter is structured as follows. We briefly introduce our conceptual framework before we summarise the theoretical foundations of innovations in technologies and firms in the next section of this chapter. Section 3 describes the pioneering activities and first innovation indicators that already broadened the empirical perspective on innovations and continues with indicators that allow to describe innovation systems and their performance in a national and international comparative perspective. New data sources and upcoming target areas are discussed in Sect. 4, while Sect. 5 focuses on recent developments and tries to look what is immediately ahead of us. Section 6 contains the summary and conclusion.

As a conceptual framework we consider four different, but interacting dimensions. They have shaped the demand for and evolution of the indicators in the last 50 years (Fig. 1).

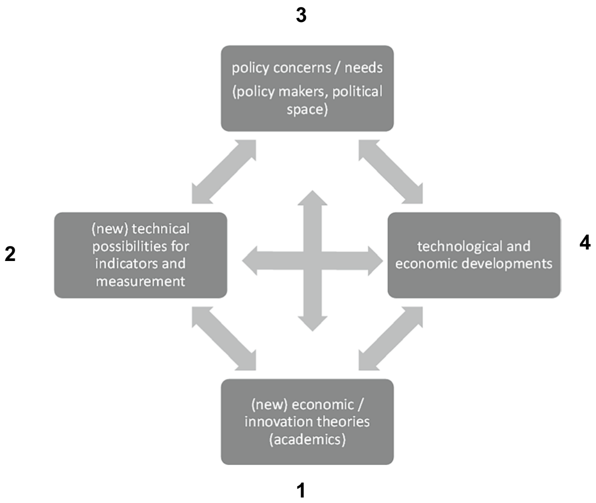

Fig. 1 Framework for the evolution of indicators. Source: Own representation

Economic and innovation theories provide a *first* dimension on the development of innovation indicators. Important examples comprise the replacement of a linear understanding of innovation by a systems perspective, the realisation of different types of innovation systems and their significance, such as national, regional or technological systems (Warnke et al. 2016). Other contributions deal with research on the functions of innovation systems offering new opportunities for innovation analyses (Bergek et al. 2008; Hekkert et al. 2007), or the emergence of transition theories, providing a multi-level perspective on innovation (Geels 2002). For a systematic elaboration of empirical evidence supporting such new concepts, specific indicators are needed.

Second, new technological possibilities to generate data offer an additional perspective for the elaboration of innovation indicators and the empirical analyses. The tremendously increasing computing power or the availability of huge data sets (Big Data) not only in (natural) science, but also on social and economic systems, are important examples illustrating these trends (Glänzel et al. 2019).

The *third* dimension comprises the political perspective. Needs and concerns in the political space call for objective, and if possible, quantitative measures and assessments for informing policy-making. Examples include the discussions on the international competitiveness (Fagerberg 1988; Freeman 2004) of Europe in the light of emerging economies in Asian countries. This trend started in the 1970s with a focus on Japan and for a number of years has been replaced by the development of China as an economic super power. This was complemented by increasing concerns as to the contribution of technologies and innovations to solve societal problems (Edler and Fagerberg 2017). Other recent examples include discussions on technology sovereignty (Edler et al. 2020) of nations or regions considering trade restrictions, breaking down of supply chains, or the dependence on energy supply and raw materials from just a few countries.

The *fourth* dimension concerns technological and economic developments. Examples encompass the rapidly growing biotech sector since the 1980s (Reiss

2001), the ongoing digitisation of basically all industry sectors (Oztemel and Gursev 2018) or recently the emergence of new technological paradigms, such as quantum technologies. Exemplary economic developments embrace, for example, the growing global influence of China (Frietsch et al. 2019), the dominating role of a few global IT companies, or the issue of economic perspectives of countries in the Global South. In order to track such developments, suitable indicators are required.

2 Theoretical Foundations of Innovation Processes

2.1 What Is an Innovation Indicator?

Before we clarify what is an innovation indicator, we first need to define what we see as innovation in the context of our discussion. In other words, we need to define our subject before we can look for means to measure and describe this subject. Schumpeter (1942, 1997 [1911, 1934]) himself did not really define innovations. He only delivered a process definition using five categories of "new combinations", namely new products, new production processes, new markets, new input sources or new positioning in markets.

First globally accepted and codified definitions of innovation at the OECD (1992, p. 31) and also previously used definitions were restricted to technological product or process innovations. These definitions led to (or were inspired by) a focus on the manufacturing industry and a corresponding production of data and indicators. It served well for a long time, but since the second half of the 1990s, in particular, it has repeatedly encountered broad criticism within empirical and theoretical innovation research (Coombs 2003; Gallouj 1997, 2002; Hauknes 1998; Miles 2004; Sundbo and Gallouj 1998; Tidd and Hull 2003), since a superficial focus exclusively on technical innovations no longer seemed appropriate due to the growing importance of the service sector within Western industrialised countries.

In consequence, the OECD adapted the definition of what innovations are. However, similar to Schumpeter the definition is also a process—or in this case an output-oriented—definition. The OECD provided a general definition, describing innovation as the result of different kinds of processes:

> An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations (OECD, Eurostat 2005, p. 46).

Following the OECD approach, defining innovation as the process of the generation of new outcomes or the outcome of such a process itself, we continue with the definition of what an innovation indicator is.

Many analytical subjects, especially when they are of an abstract, multidimensional, or in other ways complex form, cannot be directly observed or measured. These are the so-called latent constructs or latent variables in economic and management research. To monitor, assess, compare (benchmark) or measure them, it is therefore necessary to resort to so-called indicators, which—as their name clearly suggests—provide an indication of the underlying concept to be measured (Grupp 1998). In essence, these are factors or variables of which one knows or at least believes to know that they are closely linked to the subject of interest and therefore allow conclusions to be drawn about the actual target variable. These indicators can then be measured, counted or recorded in some other way.

> If 'measurement' is the formal assignment of numbers to circumstances, comparisons will be necessary. [...] The properties which need to be noted when comparing the process investigated against an archetype are termed indicators. If, simultaneously, various indicators are considered plausible (which is standard practice in innovation economics), it can be stated that various operational definitions and hence various measurement processes are available to innovation processes or to their component parts. (Grupp 1998, p. 31)

Besides what Grupp emphasised in this definition of an indicator, namely the link between the measurement and the circumstance itself, the operationalisation of the measurement in form of an indicator and its validation are inevitable. Furthermore, it should always be kept in mind that the indicators are only indications and therefore a means to analyse the end. It should not become an end in itself. In this respect, the measurement itself might have an impact on the validity of the relation between the subject (or circumstance, as Grupp put it) and the indicator. For example, scientific journal publications were seen as an indication of scientific competences, assuming they add to the current scientific knowledge. In addition, their quality as well as scientific perception or visibility was to be reflected by the citations they receive in papers by other researchers. In times when the numbers of publications exploded and when the marginal added value of the majority of these publications is diminishing, the former relation of the subject/circumstance (namely scientific contribution) and the indication by bibliometric data might require a reconsideration.

We leave the answer to these questions to other papers, but would like to stress at this point that indicators are a means and not an end in themselves and should be carefully selected and used based on scientific grounds. Otherwise artefacts and mistakes might be the outcome of indicator studies instead of empirical evidence. The fact that, for example, social media data is available at all does not mean that it is an adequate indication of social impact of scientific or technological activities. Proper conceptualisations and especially validation studies of these conceptualisations are mandatory. A task that nowadays sometimes seems to be neglected, when data availability appears to drive the conceptualisation instead of an operationalisation of the concepts based on proper data and indicators.

2.2 The Development of a New Discipline: Innovation Studies

In this part of the chapter we describe the innovation indicators along the dimension one and two of our indicators development scheme (see Fig. 1) as this more or less reflects the chronological order of the historical development. The first dimension is that of innovation research and economic theory. The second dimension is that of data availability and accessibility as well as decreasing technical obstacles due to increasing computing power. To start with, we address the first dimension and especially the paradigm we would like to call the "R&D paradigm" as the indicators at this time are centred on the R&D activities—either the R&D inputs like expenditures or personnel, or the output in form of patents or publications. The "R&D paradigm" bore innovation indicators at the firm level as well as at the macro-economic level to analyse the (linear) innovation process that spans from directed and structured R&D activities to inventions and via new technologies, processes or services to commercialisation and diffusion of these inventions, which then become innovations (Godin 2006; Grupp 1998; Schmoch et al. 2000).

The theoretical basis of innovation economics was elaborated by Joseph Schumpeter as early as 1911 (Schumpeter 1942, 1997 [1911, 1934]). In the 1960s and 1970s, economic theories on innovation were developed by, e.g., Gibbons and Johnston (1974), Gilpin (1975), Mansfield (1968), Merrifield (1979), Nelson and Winter (1977), Price and Bass (1969), Rosenberg (1976), Schmookler (1966), Utterback and Abernathy (1975) or Weingart (1975) who laid the conceptual ground for innovation systems analyses, innovation economics and innovation policy as well as innovation policy analyses. As innovation economics contribute to describing and analysing economic prosperity, the theories induced a strong need for empirical verification and stimulated the conception of innovation indicators and innovation monitoring.

However, the broader establishment of innovation economics as an independent sub-discipline of economics was first initiated by Christopher Freeman with his book "The Economics of Industrial Innovation" (Freeman 1974). Therein, he describes the growing relevance of innovation for economic prosperity by citing various examples such as chemistry, automobiles or electronics. The illustration of the theory by empirical examples was decisive for the broad diffusion of Freeman's approach that he developed further in his later publications (e.g. Freeman and Soete 1997). For him, research and development (R&D) played a crucial role. For example, he showed the trends for the expenditures on R&D in the 1980s for 50 leading countries. He also provided a table on inputs and outputs in research, invention, development and innovation and listed various items, which could be used to measure these activities. He therefore introduced innovation indicators. For instance, he suggested the working time of researchers or their remuneration, research papers, patents or technological papers as possible measurable quantities.

Freeman had established the Science Policy Research Unit (SPRU) at the University of Sussex as early as 1966 (Fagerberg et al. 2011) and even before that he got involved in the OECD in order to achieve a comparable documentation of the R&D activities of countries that led to the Oslo Manual—setting the standard at that time and continuing to do so today. His work had enormous influence on the field, but also on institutions worldwide, among them Fraunhofer ISI.

While in Solow's (1956) economic growth model the technological change was external and simply explained by the unexplained component in the model, Mansfield (1968) and later on Romer (1990) endogenised the technological progress and established it as a relevant component in macro-economic modelling, giving especially way to analyses of the technological competitiveness of countries, regions or sectors. At about the same time, analyses at the micro-economic level of the firm began to focus on effects of innovations on firm performance and competitiveness (Crépon et al. 1998; OECD 1996; Teece 1986, 1998). R&D expenditures became the main input indicator to measure and assess the efforts to achieve new scientific and technological knowledge that lays the foundation of this competitiveness, both at the level of countries and at the level of firms. At the throughput level of the innovation process, scientific publications and patents became the core indicators. The main advantage of these indicators is not only the direct comparability of countries (or science and innovation systems, respectively), but also that they enable putting a focus on scientific disciplines and technological areas—even down to individual technologies. In the early years a focus on countries, regions and technologies was mostly taken, while in the 2000s a shift towards analyses of organisations and individual actors in the system became more widespread—among other factors, this trend was definitely influenced by the innovation systems heuristic (Edquist 1997; Lundvall 1992; Nelson and Winter 1982) and its actor orientation.

Box 1: One Example of Organisational Development in the Field of Innovation Indicators: Fraunhofer ISI's Pathway to Indicators

The founder and first director of Fraunhofer ISI, Helmar Krupp, was in close contact with Christopher Freeman. In the first years of the institute's activities, the work was primarily qualitative, e.g., the conception of political measures of initiating R&D activities in small and medium-sized enterprises, or based on limited surveys, e.g. users of energy efficient houses. The general situation at that time is well characterised by a seminar of the German Federal Ministry of Research and Technology (BMFT) with international participants in 1977, where most of the contributions were qualitative (Stroetmann 1977). The only innovation indicator was research and development expenditure (R&D) by countries or by specific industrial sectors. The contributions to patents dealt with the relevance of patent protection for innovations, but not with patent statistics.

Early contributions by Fraunhofer ISI to innovation indicators are Gielow et al. (1982), suggesting improvements of the German survey on industrial R&D, Kuntze et al. (1975) with basic considerations on using patent statistics as an innovation indicator, and Legler (1982b), analysing the German chemical industry based on foreign trade and patent statistics, where the patent data were provided by the US-American and the German Patent Office. The further development of innovation monitoring and innovation indicators was stimulated by a series of small international workshops. For example, at a seminar in Karlsruhe in 1985, researchers from Sweden, Germany, Portugal, Japan, the USA, the Netherlands and Great Britain discussed topics such as bibliometrics, the relation of patents and R&D, patent statistics, technometrics, foreign trade of research-intensive goods or the international comparison of research-intensive technologies such as robotics, genetic engineering or fibre-optics (Grupp and Legler 1987). Similar workshops followed in 1988, 1990, 1991 and 1993 (Grupp 1992; Sigurdson 1990). Due to these workshops, various international co-operations were initiated such as Noyons et al. (1994) or Schmoch et al. (2003).

As regards the output side of the innovation process, the commercialisation of all these efforts is of interest also from an indicators perspective. From a rather macroeconomic view, international trade was the main indicator, while at the microeconomic level the introduction of new products, processes or services was taken as an indication of the innovation output. A differentiation of the analytical models by sectors, technologies or organisation type led to a better understanding of the innovation process as such and provided insights into the complexity of the processes and their effects. Distinctions between R&D-intensive sectors or technologies (see Grupp et al. 2000; Hatzichronoglou 1997; OECD 2003) as well as between knowledge-intensive businesses (Legler and Frietsch 2007) were introduced to categorise the groups and types. These were based on the insight that not all actors need to be or effectively are involved in innovation processes. Furthermore, the particular innovation processes are very different for each technology, company or sector and the categorisation helped to generalise this insight.

2.3 Paradigms of Innovation Research: Shaping Indicators

We referred to Schumpeter's work (Schumpeter 1942, 1997 [1911, 1934]) as the initiation of innovation research, focusing on the entrepreneur and his/her role as a "creative destructor". This perspective on innovation activities was later on named as Schumpeter Mark I (Malerba and Orsenigo 1995; Nelson and Winter 1982). In his later publications, Schumpeter already stressed the role of large companies and their R&D departments for putting forward innovation processes, which was later on named Schumpeter Mark II.

Since the 1960s a systemic perspective has occurred, first focusing on science systems and their competitiveness and then broadening to R&D in general—first also on the systemic level, where most indicators have their origin and later more and more also including company data at the micro-level, which allowed a better understanding of the processes themselves. This is what we referred to as the R&D paradigm (Mark II) and in which the indicator development was closely linked to the work of Christopher Freeman and his endeavours for the OECD (Fagerberg et al. 2011). In this section, following Sundbo (1997, 2001), we want to introduce an additional paradigm (we could also term it era) of innovation research, that is characterised by further differentiation and deepening of the analytical framework. From here on, we would like to rely on this differentiation of three paradigms to link the particular focal points of innovation indicator developments.

Based on Schumpeter's work, Sundbo (1997, 2001) differentiates between three "paradigms" of innovation. In addition to the "founder's paradigm" that mainly addresses the era of Schumpeter and his descriptions of the entrepreneurial innovation processes (Mark I) and the "economic paradigm" that is centred on R&D activities of large companies (Mark II) and which we therefore termed "R&D paradigm" above, he introduces the "strategic paradigm" (Sundbo 1995, p. 400) that widens the innovation definition and perspective especially to services and shifts the attention to demand-side and diffusion activities in addition to the (R&D) input.

The first of the three identified paradigms, the founder's paradigm, falls into the period of the industrial revolution and the subsequent start-up period of companies, often with a patriarchal company owner at the top. This paradigm lasted till about the end of the Second World War (Grupp et al. 2005). According to Sundbo, it is precisely these founders that Schumpeter had in mind with his analysis of the innovation system. In this first phase of innovation research, indicators played a minor role and the research was more of a qualitative and descriptive nature with the intention to understand—in Weber's sense (Weber 1972 [1922])—the process and the success factors. A focus was on the individuals and the inventions they made.

After this start-up period of innovation research, which, depending on the definition, extends into the first half of the twentieth century, the time of technological developments in modern society arose, forming a second paradigm. According to Sundbo, this paradigm is the "economic" one, in which technology and its development are in focus. Investment in research and development (R&D) drives economic growth through the generation of new technologies. These technologies develop new needs or cover existing needs. So new technologies find their buyers. During the period of this paradigm, R&D departments and public research activities are the focus of attention. The innovation process is often associated with a science or technology-push situation, where the "right" and new products will be absorbed by eager consumers/clients in demanding markets. Innovation theory is correspondingly concerned with the kind of "indicators" that can be used to measure these components. Here the focus is on research expenditures, patents or high-tech products.

Therefore, while Schumpeter's theory (1997 [1911, 1934]) clearly aimed at the entrepreneur (Mark I), within the framework of the economic paradigm with its focus on R&D (Mark II), his/her importance has receded somewhat into the background in some parts of the economy. On the one hand, large corporations emerged in which a manager or technical director did not play the same role as the entrepreneur in Schumpeter's model (Mark I). In such corporations, the fate of the individual is generally no longer tied to the fate of the company. On the other hand, it is much more important for the decoupling or the loose connection between the decision-maker and the company that the number and complexity of the tasks and the qualifications involved and competencies have increased significantly over time. A division of labour is essential within companies that want to be economically successful. This leads to specialisation and "expertise" as well as to a systematisation of the process and its organisation (Frietsch 2011; Marengo and Dosi 2003; Teece 2007). The functional division of labour creates the prerequisite for the intensification of knowledge and its importance for all work processes. This also means that innovation indicators are found that are able to describe the different tasks, the different stages of the innovation process. They also describe the role of the different actors relevant for these processes as well as the effects/outcomes of these tasks and stages.

The third paradigm, the "strategic paradigm", emphasises the shift in innovation processes to additional factors, making R&D investments still a necessary, but no longer a sufficient condition for innovation success. Since the technologies have become very complex and the supply of new technologies does not necessarily cover an open need/demand on the part of consumers, other strategies are necessary that lead to the sale of the new products and services. A science-push or technology-push situation occurs less often. A "pull situation" needs to be created, i.e. the technologies attract the consumers'/clients' attention, for example by employing marketing and other sales-promoting measures. From the companies' point of view, which are now moving into the centre of a holistic interest under the aegis of this paradigm, it is crucial to look for the ability to develop corresponding strategies and ideas about products and services that enable growth in the respective markets. The key players in this game are the managers and decision-makers in companies who use their skills and abilities to guide the companies' fortunes. At the same time, however, the employees are also moving further into the centre of the analyses because they generate ideas, contribute their knowledge and thus create the prerequisites for innovations.

In this third (and still ongoing and open-ended) paradigm and the shift of focal points of innovation analyses, new needs and perspectives of innovation indicators arose as well, mainly driven by a differentiation of innovations and innovation processes. Sundbo's (1998, 2001) thesis is that the image of the decision-maker and thus also of the innovation process has changed significantly over time. Neither the image of the classic entrepreneur, who was seen as the "creative destructor", addressing the market needs through "new combinations", nor R&D expenditures or other mainly input-driven factors are the main driving forces in the innovation process any longer. Teece (1986) makes a similar argument when he claims that the innovation process has changed significantly. The increased complexity and the necessary broader knowledge require a different approach to the research and development process and then also imply different forms of organisation. Although the research process is still targeted, it is associated with significantly greater uncertainties and also with significantly larger investments. The latter, in particular, means that not only increasing productivity, but also increasing R&D efficiency is required to ensure competitiveness. In consequence, concepts like open innovation (Chesbrough 2003; von Hippel 1988; von Hippel and Krogh 2013) attract the interest of innovation researchers and managers alike as the insight diffuses that not only effectiveness, but also efficiency in the knowledge-creation processes is of the utmost relevance. Absorption (Cohen and Levinthal 1990; Teece 1986), transfer from public research to industry (Etzkowitz and Leydesdorff 1995; Schmoch et al. 2000), active external knowledge sourcing, for example, from international markets (Arundel et al. 1998; Thursby and Thursby 2006; UNCTAD 1992), as well as knowledge exploitation (Chesbrough 2003) have been accounted for by innovation scholars, managers, and also by policy makers since then.

To sum up, while in the first phase of the "founder's paradigm" hardly any quantitative indicators were used, but rather qualitative analyses of companies and processes, the economic paradigm shifted the attention towards—mostly macro-economic—quantitative indicators. This is where the OECD and its focus on R&D activities played a crucial role. For the description and the analysis of the innovation processes under the "strategic paradigm", additional indicators for collaboration types, knowledge exchange or innovation processes outside the manufacturing sector were needed. Indicators to assess the flow of knowledge between science and industry or industry and industry, international knowledge flows, the use of knowledge by innovators, or the particular knowledge and technology transfer gained attention.

3 Pioneers in Innovation Indicators: Early Activities of the Community

3.1 Main Indicators (R&D, Patents, Foreign Trade)

As outlined above, the early 1970s saw developments in innovation studies to compare the competitiveness and performance of science and innovation systems at the different levels, mainly at the country and later on also at the regional or technological level. Therefore, one focus was a better understanding of industrial R&D as well as innovation systems as a whole. While early indicator developments had mainly focused on the science system and its contributions to innovations in general, the era of the "R&D paradigm" achieved not only a much broader conceptual understanding of innovations and innovation processes, but also a huge differentiation and systematisation of indicators for their empirical underpinning.

The analysis of *industrial R&D* was a major topic already in the analyses of Freeman (1974). Industrial R&D was examined by many authors, such as Majer (1978), Griliches (1979), Caulcutt (1992) or Grenzmann et al. (1991), but already Schmoch et al. (1988) showed that R&D data are only available on the aggregate level of industrial sectors, whereas for specific technologies rarely reports were on hand. Therefore, R&D data are primarily useful at the aggregate level. R&D indicators refer to the first dimension of our indicator scheme (Fig. 1), i.e. policy concerns.

For achieving a finer level of aggregation, *patents* were suggested as innovation indicators quite early on (e.g. in Freeman 1974; Maclaurin 1954). The prospects of patent indicators were discussed in Kuntze et al. (1975), but still on a very basic level with some aggregate data provided by the German Patent Office. Many concerns as to the validity of patent indicators existed. They achieved a broader legitimation by Griliches (1981), whose article was a real turning point for the acceptance of patent indicators. Decisive progress in the use of patent indicators was achieved by using electronic databases. Faust and Schedl (1984) used an in-house version of the international patent database INPADOC, Narin et al. (1987) established an in-house version of the patent database of the USPTO (US Patent and Trademark Office). Narin and his colleagues introduced a variety of new indicators such as patent citations or citations of non-patent literature (NPL) to patents. The Science Policy Research Unit

(SPRU) at the University of Sussex also worked with an in-house version of a USPTO database and contributed basic methodological papers (e.g. Pavitt 1985) and various patent-based economic analyses (e.g. Patel and Pavitt 1991).

In Germany, Fraunhofer ISI began broader patent analyses with the access to the German patent database PATDPA, which the host STN provided as an online database. Schmoch et al. (1988) discussed various topics such as the comparison of national and international patent databases, the conception of patent search strategies, the use of foreign patent applications, the grant rate, the team size of inventors or the citation frequency, and the link of patent indicators for different technologies to R&D data, publications, technometrics or foreign trade. This very basic analysis was largely ignored, as it was published in German. However, by various follow-up publications, such as Schmoch et al. (1991), Grupp et al. (1996) or Grupp and Schmoch (1999), the use of international patent statistics beyond the use of USPTO data was taken up by many research groups and international institutions such as the OECD or the WIPO, among them the Triadic patent approach (see box below) or the classification of technology fields published by the WIPO (Schmoch 2008). Despite some limitations such as the focus on patentable technologies or underrepresentation of small and medium-sized enterprises (SMEs), patent indicators became broadly accepted, as they allow for a very detailed definition of specific technologies, balanced country comparisons, the analysis of enterprises, the transfer activities of academic institutions, etc. Patent indicators offer to retrace technological developments and are often produced in reaction to policy concerns, thus cover dimensions one and two of our indicator development scheme. They are also used for supporting new economic theories (dimension three, Fig. 1).

Patent searches for statistical analysis are mostly based on codes of the International Patent Classification (IPC) or keywords in the title, abstract or claims of the patent documents. Due to more powerful computer systems, it is now possible to define strategies by text mining in the complete text which opens new possibilities of analysis (we will come back to this further below). Thus, in the recent version of the Handbook of Science and Technology Indicators (Glänzel et al. 2019) five chapters on patents deal with text mining approaches.

Box 2: Country Comparisons in Patent Statistics

A major issue of patent statistics is to describe the technological competencies of countries in country comparisons in an appropriate way. Country comparisons at a specific patent office imply a strong advantage for the domestic country linked to that office.

1. A first suggestion to solve this problem was made by Soete and Wyatt with the indicator *RTA (Revealed Patent Advantage)*. However, this indicator only captures relative, but not absolute comparisons.
2. Gerstenberger (1992) used all patent applications which are applied in at least two countries, thus have a *family size of at least two*. This concept was adopted by the World Intellectual Property Organisation (WIPO) (see, e.g., WIPO 2019, p. 123). However, in specific analyses for technologies,

the patent numbers of Japan appeared to be overestimated (Schmoch and Khan 2019, p. 916).

3. A further suggestion were the so-called *triadic patents* (Grupp et al. 1996), which focus on applications filed in the USA–Europe–Japan triad. This approach was taken over by the OECD and used for many years. But it became increasingly obsolete in the late 1990s, as the economic power of China and South Korea grew.
4. *The IP5 concept* was suggested by the OECD. There, patent applications to the five major patent offices in the world are considered: the EPO, the USPTO, the JPO, the SIPO and the KIPO (OECD 2015, p. 20). In this concept, the threshold for Southeast Asian countries is quite low, as e.g., the step from China to Japan is smaller than that from Europe to the USA. In consequence, these countries are overestimated in analyses for specific technologies (Schmoch and Khan 2019, p. 916).
5. *Worldwide Patent Counts* were suggested by the OECD and some universities (de Rassenfosse et al. 2013), which are implemented as counting patent families, including singletons (Maraut and Martínez 2014; Martinez 2011). This needs to be seen very critically as it assumes that any patent at any office has the same technological value. In reality, patent offices differ immensely, for example in the quality or inventive step of the patents they accept, the newness of the inventions (worldwide vs. national prior art) and a number of other dimensions. In addition, it is not possible to analyse emerging technologies (Schmoch and Gehrke 2022). These concepts tend to strongly overestimate the effects of national filings and therefore ignore the structural and legal as well as market differences of patent jurisdictions. The technological competitiveness of countries like South Korea or China is overestimated based on these approaches and on most of the other conceptual approaches.
6. *Transnational Patents* were suggested by Frietsch and Schmoch (2010). The concept is defined by patent families which comprise either European applications and/or international applications (PCT applications), thus families with a substantive size. According to the present state of knowledge, this approach seems to lead to appropriate results (Schmoch and Khan 2019, p. 916). This concept follows the same idea as the Triadic patent approach, which addresses a balanced and internationally comparable market where mainly the technological competitiveness is decisive beyond national or legislative idiosyncrasies. This concept for patent analysis allows to construct the conditions for empirical analysis and comparison of national systems based on technological profiles. The concept makes use of the effective filing routes for most of the companies and technologies, when they are to be filed abroad. Empirically it was shown that in the vast majority of cases, companies tend to use at least one of these filing routes of EPO or PCT. According to the present state of knowledge, this approach seems to lead to internationally comparable results (Schmoch and Khan 2019, p. 916) that are at the same time correlated to other relevant innovation indicators such as R&D expenditures or exports (Frietsch et al. 2014, 2017).

Foreign trade data are standard for a variety of economic analyses, e.g. the annual analysis of the trade balance of countries. The foreign trade data become innovation indicators, once they are linked to R&D. An important activity in the context of R&D was the differentiation of industrial goods by R&D intensity. As early as 1982, the Institute of Economic Research of Lower Saxony (Niedersaechsisches Institut fuer Wirtschaftsforschung, NIW) defined a list of goods according to the foreign trade classification SITC, differentiated by high and medium technology (Legler 1982a). The European Commission published a similar list in 1982 (Kommission der Europäischen Gemeinschaft 1982) and the OECD in 1985 (OECD 1985). Further details can be found in Grupp and Legler (1987). This definition of R&D-intensive goods, high-level technology goods and cutting-edge technology goods was regularly updated (e.g. Legler and Frietsch 2007). An early report based on this classification is Legler et al. (1992). This classification allows for a characterisation of countries by the R&D intensity of goods. In addition, it analyses how economies with specific R&D profiles respond to business cycles.

Based on the classification of goods, it is possible to characterise sectors by R&D intensity. In the case of service sectors, a classification by knowledge intensity is made on the basis of the shares of qualified staff (Legler and Frietsch 2007).

Foreign trade data are documented to fulfil the demand policy and inform decision-makers to allow for analyses of national competitiveness (first dimension of our indicator development scheme, see Fig. 1).

3.2 A Further Broadening of the Scope: Micro-Data Analytics and Additional Indicators for Particular Parts of the Innovation Process

The informational value of patents and R&D as innovation indicators, which essentially reflect the strong focus on inputs and throughputs of innovation processes, was challenged already in the 1980s and 1990s by several authors (e.g. Kleinknecht et al. 1993, 2002; or van der Panne 2007). They suggested to shift the attention to outputs and, for example, to identify new products introduced to the market by statistically evaluating trade journals. The authors achieved quite convincing results, but the challenge of this approach was to classify the products in an appropriate way and to identify comparable trade journals for different countries. Due to these restrictions, this approach did not establish itself to a greater extent. However, the introduction of new products was included in the Oslo Manual (OECD 1992) and incorporated standards for innovation surveys.

Due to the political interest to better understand the competeveness of firms within innovation systems, further innovation indicators for enterprises are generated by regular broad surveys. The Community Innovation Survey (CIS) is the reference survey on innovation in enterprises (OECD, Eurostat 2005). On this basis, it is possible to compare the innovation activity of most countries of the European

Union (Eurostat 2020). For each country the innovation activity in specific sectors and the development of innovation in time can be examined (Rammer et al. 2021). In order to comply with the regulatory requirements and also to respond to the needs of various users, Eurostat together with the member countries develops for each round a standard questionnaire—Harmonised Data Collection (HDC). In addition to core mandatory questions, each survey wave includes varying variables, e.g. environmental benefits of innovation. Thus, many aspects of innovation are covered.

The EU Member States first introduced the survey in 1992 and since then it has become the regular biennial data collection. At present, the survey is carried out in the EU, EFTA and the EU Candidate Countries. Other countries such as South Africa use the CIS as well. Most of these national surveys build on the Oslo Manual of the OECD, which defines the standards for innovation surveys and provides the "guidelines for collecting, reporting and using data on innovation" (OECD 2018). The CIS activities fulfil requirements of the political space (Dimension three of our indicator development scheme, Fig. 1).

A further approach to use production statistics are broad enterprise databases such as ORBIS (Moody's), Crunchbase or Hoovers (Dun & Bradstreet). Therein, the enterprises are classified by economic activities according to classifications such as NACE. Due to improved software and hardware, it is possible to link patent and enterprise databases and to analyse innovation activities by industrial sectors (Neuhäusler et al. 2016; Schmoch et al. 2003. This approach can be associated with dimension two of our indicator development scheme (Fig. 1), namely new technical possibilities for indicators.

Additional data sources of innovation indicators are also available for foreign trade, R&D expenditures, production or labour force. For example, the UN Comtrade database, the Business R&D Expenditure (ANBERD/STAN) databases of the OECD, the production and sales database of the OECD or the ILO Labour Force database (ILOSTAT) provide additional data, mainly for macro-economic analyses of innovation systems.

A further concept for measuring technological performance is technometrics, first described in Grupp et al. This approach aimed at a holistic understanding of the performance of a country (or region) as regards the generation of a technology. For this approach, some technologies such as solar cells, laser beam sources or industrial robots were selected in a first step. Then, characteristic performance features for these technologies were identified based on a literature survey and interviews with enterprises and scientists. In the final step, the level of these performance features was collected for different countries. This way, the performance of a country in a specific technology in comparison with others could be determined and in particular the features with high and low performance. This approach proved to be useful for analysing the situation in a specific technology field. However, the identification of relevant features and the collection of related data are quite laborious, so that a comparison of many technologies and countries is challenging. Therefore, the use of technometrics is quite limited. Technometrics help to describe technological developments, i.e. they can be categorised in dimension four of our indicator development scheme (Fig. 1).

Another innovation indicator for enterprises are trademarks, for which basic conceptual work started at the beginning of the 2000s (e.g. Mendonça et al. 2004; Schmoch 2003). At that time, the innovation process and its outcomes were well described with the indicators at hand, whereas it was not possible to analyse the diffusion and implementation—which makes the crucial difference between an invention and an innovation—in a satisfactory manner. The introduction of trademarks as innovation indicators was intended to close this gap and to push the frontier of innovation indicators further. Whereas patents show the intention to introduce a new product into the market, trademarks indicate that the product already is on the market. The classification for trademarks is quite coarse and comprises only 34 product classes (Nice Classification). In consequence, the analysis of products by patents is generally more differentiated than that by trademarks. Nevertheless, trademarks describe a different aspect of innovations with a closer link to markets and diffusion. In addition, Neuhäusler et al. (2021a) suggested a method to further classify and differentiate the categories addressed by trademarks employing the mostly standardised keywords of the Nice Classification.[1]

In addition, it is also possible to apply trademarks for services with 11 service classes, a dimension which cannot be captured by patents. Therefore, it is feasible to analyse service enterprises such as banks or insurance enterprises by service marks (Schmoch and Gauch 2009). Furthermore, the economic performance depends not only on technology, but also on the quality of services linked to the products. Thus, a combination of patents and service marks offers additional analytical potentials than a simple patent analysis (Mendonça et al. 2019). Again, trademarks are used for describing technological developments, which, in contrast to patents, indicate that the technologies are deemed ready to be introduced into the market.

4 Indicators for Innovation Systems

The discussion of national systems of innovation (NIS) brought about a decisive change in the use of innovation indicators (Freeman 1987; Lundvall 1988; Nelson 1993). The enlarged view on national systems instead of enterprises and individual technologies proved to be necessary, as many observations in the context of innovation could not be explained solely by the activity of enterprises. Rather, the contribution of institutions of education and research, of government bodies, intermediaries, financial institutions, the structure of the socio-economic environment, the legal system, etc. are also relevant for the innovative performance of a country. In consequence, many additional indicators and their interaction have to be taken into account. In the following section, the most important additional indicators are described.

[1] https://www.wipo.int/classifications/nice/en/

4.1 Data Sources for Indicators

For measuring the performance of universities and research institutes, a set of publication indicators was developed. Garfield (1955) built a publication database including the citations on publications very early on. This was the origin of the Web of Science (WoS). The company CHI Research (Philadelphia) owned by Francis Narin used this database already in the 1970s (Frame et al. 1977) for bibliometric analyses in order to compare the performance of institutions and of national science systems. A broader introduction to innovation research was achieved by a series of conferences of the Centre for Science and Technology Studies (CWTS) at the University of Leiden, Netherlands (van Raan 1989). At the beginning, CWTS was confronted with various concerns as to the validity of bibliometrics or the citation analysis of publications. They succeeded in developing a sound methodology of bibliometrics (van Raan 2005). The broad acceptance of bibliometrics was the consequence of the extension of new public management at universities and, linked to that, the need of performance indicators of science.

Around 2004 the database Scopus by Elsevier was established in competition to the Web of Science (WoS) of Garfield, by then provided by the information broker Thomson Reuters and in the year 2017 taken over by Clarivate Analytics. Both databases have a broad coverage of international publications, about 14,000 journals in WoS and 22,000 in Scopus (Bauschmann and Ahnert 2016). Therefore, they are not only useful for citation analysis, but also for the analysis of publication trends of countries and institutions. Since 2018 also the free-of-charge available database Dimensions by Digital Science added to the available and curated bibliometric sources as well as the Open Alex Database that emerged out of Microsoft Academic Graph after it was discontinued. Naturally, many publication databases for special scientific fields are available, for example MedLine, Compendex, and also for particular document types such as arXive in the case of pre-prints. However, most of these latter listed publication databases only provide bibliographic information, while bibliometric data (including citation information) is only covered by a small number of data sources. The steadily developing new ways of bibliometric analysis, documented, e.g., in journals such as Scientometrics, are induced to a large extent by improved technical possibilities to conceive and exploit databases (dimension four of our indicator development scheme, see Fig. 1).

For innovation analyses, not only the performance of the science system of a country is relevant, but also the link between science and technology, which will be discussed in more detail in the following section of this chapter. In the case of science-based technologies, the parallel observation of patents and publications proved to be one insightful approach (e.g. Schmoch 2007). Furthermore, it is possible to analyse which university publications are frequently cited by enterprises (Tijssen 2006) or which were published by authors affiliated to companies (Krieger et al. 2021). The number of citations in patent examination reports is a good indicator for the science-linkage of a technology (Narin et al. 1997; Verbeek et al. 2002). For analysing technology transfer, the patents of universities are frequently employed indicators (e.g. Dornbusch et al. 2013; Neuhäusler et al. 2021a). For this type of analysis, patent and publication databases are linked. More recently, standard-essential patents and standard-relevant publications have gained attention for analysing transfer and market developments (Blind 2004; Blind and Fenton 2022). A further aspect is international collaboration in science (Leydesdorff and Wagner 2008). A central discussion in the context of national systems of innovation is the interaction of enterprises, universities and governments (Leydesdorff and Etzkowitz 1998). Systemic improvements are to be achieved where different actors or sub-systems interact—this is the basic assumption of these analytical approaches. For each of the sub-systems, particular indicators are used—for example, publications in the science system or patents mainly for industrial technological innovations—but at some point these indicators overlap or play a particular role in describing the activities of the sub-systems that go beyond. Examples are co-publications (see above) or co-patents of science and industry. Academic patents (Lissoni et al. 2008; Neuhäusler et al. 2021b)—these are patents invented by staff-members of universities or public research organisations, but not necessarily filed by these organisations—or academic spin-offs (Frietsch et al. 2021) are additional examples where the classical focal tasks and therefore also focal indicators span over the boundaries of the sub-systems.

In the case of publication databases, online versions of the Web of Science (WoS) or Scopus are available, but therein sophisticated citation analysis is not possible on a large scale, as many of the indicators use expectancy rates, field-specific indicators or organisation- or author-specific normalisations (e.g. exclusion of self-citations) as the basis for the calculations. In addition, data cleaning, data treatment and especially data linking with external sources are much harder in web-based applications than in the case of raw data access.

4.2 New Target Areas and Analytical Differentiations

A slightly different perspective arose from science and technology analyses, however, using similar data sources. The relation of science and technology has always been a major topic of analysis in innovation research. Already in the 1960s, various retrospective studies were conducted to assess the impact of basic research on technological innovation. In particular, the US-American studies called "Hindsight and Traces" had a relevant influence on science policy. An early indicator-based study was provided by Narin et al. (1987), which considered references to publications in patent search reports. A further survey-based, important study was performed by Mansfield (1991) looking at the impact of scientific research on industrial innovations. A famous theoretical contribution, why enterprises conduct basic research, was made by Rosenberg (2010). Rappa and Debackere (1992) described the interaction of enterprises and academic institutions in science-based technologies.

This line of research became more precise and tangible by the use of innovation indicators, in particular by specific forms of patent and publication indicators and their combination (Schmoch 1997). In this context, publication indicators are not used for the assessment of universities and research institutes as in bibliometrics, but for the analysis of scientific research, so the subject of research instead of the process or output is the centre of interest. For instance, Schmoch (2007) could describe the parallel development of science and technology over long periods and show the substantial delay between scientific discoveries and their broad implementation into technology (see also Moed 2017).

A phenomenon of the last years is the increasing number of science-based technologies such as nanotechnology, graphene and other two-dimensional materials, artificial intelligence, electrically conducting polymers, plant biotechnology, high temperature superconductivity, light emitting diodes (LEDs), fuel cells, CRISPR-Cas technologies or improved computer storage systems. A typical observation of a parallel analysis of patents and publications is that in the early years of a science-based technology, the academic research is focused on (oriented) basic research and with the intensified search of industry for specific applications, the academic research is increasingly oriented on applications as well. Thus a direct link between science and technology and its development in time can be shown (see, e.g., Schmoch and Thielmann 2012).

Since about the end of the 1990s, a major topic of the relation of science and technology are the university-industry relations. Most of these papers are indicator-based (Perkmann et al. 2013) and aim at assessing the link between academic research and economic impact. A trigger for this broad activity was an article by Meyer-Krahmer and Schmoch (1998) analysing the university-industry relations as to major mechanisms, advantages and disadvantages for universities as well as differences by scientific fields.

In recent years, there has been an increasing interest in knowledge transfer from academic research to society. This is monitored with indicators such as memberships in political advisory councils, consultancy for social institutions, publications in non-scientific journals, etc. and can be observed in many countries. Thus all scientific disciplines, not only the engineering and natural sciences, are involved. For analysing this type of interaction, new indicators have to be conceived. A part of this new approach comprises the so-called altmetrics (Thelwall 2019), but additional tools will be needed for describing the full spectrum of transfer activities.

In the 1960s and 1970s, innovation indicators were primarily oriented on research-intensive technologies. In the middle of the 1990s, innovation in service industries was complemented. However, it was attempted to transfer the methodology for production technologies to services which proved to be problematic. For example, it is possible to compare biotechnology and mechanical engineering on the basis of R&D intensity, but the structures in services such as banking, accommodation, transport logistics or medical treatment are so different that a meaningful comparison based on R&D expenditures is difficult.

One approach to overcome this inadequacy is the concept of knowledge intensity instead of R&D intensity. Knowledge-intensive companies or services are characterised by high shares of highly qualified personnel—most often university or college graduates—whereby these high qualifications play a major role in the value creation of these companies/sectors.

This is even more complicated in the case of digital business models or platform economies, where the platform provider only acts as a broker with a huge market power, but does not provide the service or the product itself. Digital business model indicators to assess their innovativeness and/or their contribution to innovation processes are to a large extent missing.

In the last 15 years or so, the character and meaning of critical technologies in the economy and society have changed. A number of key technologies are much more pervasive across a number of other technologies and domains and thus impact more generally and comprehensively on broad aspects of the economy and society compared to previous critical technologies. For example, information technology has developed into a generic field which is relevant for many other areas such as mechanical engineering, the automotive industry or biotechnology. For the description of this development, new derived indicators are needed. Another topical development is the increasing relevance of biotechnology for practical applications in industrial processes, materials, agriculture or pharmacy. Again, new indicators are needed to encompass the effects more appropriately.

5 New Data Sources, New Data Analytics: Nature, Opportunities and Limits of New Indicators and Measurements

At the beginning of the new century the framework conditions for innovation indicators began to change massively. In about the middle of the first decade a new methodological paradigm began to diffuse that was driven by what is nowadays called Big Data. While up to the middle of the 2000s data access was very expensive—both in terms of fees and in terms of transaction costs—a diffusion of a number of data sources changed the picture completely. First of all, it was the accessibility of patent data that completely changed the landscape—especially the PATSTAT[2] database provided by the EPO, but also the inauguration of the bibliometric database Scopus by Elsevier, which appeared on the scene as a competitive product to the so far—more or less—unique bibliometric data source of the Web of Science, then owned by Thomson Reuters.

Patent data was used by several innovation scholars worldwide, but the exploitation of the analytical potential was seen to be too limited so that several users and scholars asked for better data and broader data access. A first conference[3] was held in Geneva in September 2003 as a start of a series of conferences where user needs were discussed. This was one of the milestones in the direction to the first release of

[2] The official name of PATSTAT is “EPO Worldwide Statistical Patent Database”.

[3] https://www.wipo.int/meetings/en/topic.jsp?group_id=230

PATSTAT in 2005. First users started to implement PATSTAT and learned to work with large-scale relational databases. Given the technical restrictions in processing these large amounts of data, several researchers started to work with individual tables only (flat files). By the end of the decade, however, a large number of universities and research institutes in many countries had subscribed to PATSTAT and it offered completely new analytical potentials. Data cleaning, data treatment and data matching moved patent statistics from the macro-economic or technological meso-level to the micro-level of organisations (companies, universities, research institutes) or even the characteristics of individual applications (e.g. legal status, family size, citation rates). A differentiation of patent analytics became possible with micro-data access like PATSTAT.

Other data sources, for example bibliographic data on specific scientific areas like PubMed in the field of medicine or Compendex in engineering, were more and more subscribed by universities for monitoring and publication retrieval purposes and therefore became also accessible for science and innovation analytics. Additional data sources were implemented, for example, on trademarks (see Gotsch and Hipp 2012; Mendonça et al. 2004; Schmoch 2003; Schmoch and Gauch 2009), which became possible at that time as web interfaces by data owners and database providers lowered the thresholds for access to larger groups of researchers.

Most of these data sources are generated as a by-product of otherwise needed processes. In essence, innovation research analytics became possible as a secondary use of the already existing data. For some data providers commercialising the data turned out to be an additional business model. In case of IPR data, it was just an additional way of fulfilling the need for publishing and granting access, which is inherent to the IPR system. Patents are a vested right of exclusive use, but in exchange for this right, those who intend to own the rights are obliged to describe and publish their technology. Innovation statistics benefit from this IPR specific publication requirement.

In addition to those changes in relation to traditional indicators such as patents and publications, a more fundamental development took place that opened up a number of new possibilities to show innovation developments. Contrary to R&D data that requires extra efforts to collect it in large-scale surveys of (suspected) R&D conducting companies, process generated data just existed and was more frequently co-used for statistical purposes. So new business models emerged and innovation research was in demand for this new kind of data. The access to data was not the bottleneck of analyses anymore. Two dimensions gained relevance; on the one hand, an understanding of the data and its particularities; on the other hand, capabilities for data storage, data treatment and linking it to other data sources. These capabilities have recently been supplemented by capabilities to produce and use large amounts of unstructured data, mainly from web sources, from business reports, or from full-texts of patents or publications. Next to the availability of the data and the meeting of supply and demand of new data sources, all this has been possible by two additional trends. The technical evolution of treating large amounts of data with comparatively short computation times, storing them, treating them and developing ever more complex models. In addition, the demand for solid and robust innovation research results as well as evidence-based policy-making increased as more and more countries entered the innovation stage. Accordingly, policy makers all around the globe became eager to either provide the perfect framework conditions for innovation (sometimes also called innovation eco-systems) or even govern the national innovation systems with the aim of increasing the national, regional or local competitiveness. This is essentially the root of category 3 in our innovation indicators scheme (see Fig. 3).

Box 3: Reporting and Monitoring Systems

We have outlined the historical development of innovation systems and innovation process analyses as well as the evolution of indicators to measure and analyse them. From the beginning, one of the core aims, but also the core challenges was the international comparability of the data and the analyses. For this purpose, several activities of regular innovation monitoring were undertaken by the US National Science Foundation as early as 1973 (e.g. NSB 2020) or by the French Observatoire des Sciences et des Technologies since 1995 (OST 2000). Following the NSF, the OECD published in 1984 "Science and Technology Indicators", which in 1988 was replaced by "Main Science and Technology Indicators" (Godin 2003, p. 680). "Industrialised countries followed the NSF definition when they adopted the OECD Frascati Manual in 1963. The manual was designed to help countries in their measurement efforts, offering methodological conventions that allowed international comparisons". Godin (2006, p. 648).

Important activities for creating, discussing and testing new innovation indicators were efforts to establish regular innovation monitoring, which came up in several countries. For example, in Germany the annual "Bericht zur technologischen Leistungsfähigkeit Deutschlands (TLF)" (Report on the technological competitiveness of Germany) was initiated on behalf of the German Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung, BMBF). It started with Grupp and Legler (1987), a cooperation between Fraunhofer ISI and the Institute of Economic Research of Lower Saxony (NIW), and ended in 2007 (Egeln et al. 2007). Over the years, the number of participating institutes and of the indicators on different topics increased, for instance in the last report indicators on productivity, foreign trade, patents, R&D, scientific publications, technology transfer, skilled labour, women in science, technology and research, environmental technology, etc. were analysed and discussed. Since 2008, the activities of TLF have been pursued in parts of the work of the Commission of Experts for Research and Innovation (EFI) to the German government.

New data trends are already in full swing, especially the emancipation of science from commercial data providers. Public research itself started to produce data and non-profit organisations emerged with other than purely profit-oriented business models. The move from proprietary to open infrastructures continues and now covers a broader area of data sources—most visible in bibliometrics, but also in terms of other data like geospatial, mobility or company information.

Already in the late 1990s and early 2000s this development found a seedbed in public data providers like statistical offices or publicly funded service providers that made their previously non-disclosed micro-data accessible to researchers. New developments in anonymisation of individual data made data protection possible even when sharing micro-data. For example, R&D data in Europe became (partly) accessible as scientific use files became available or—more comprehensive—by on-site visits to Eurostat's data centre. Many national data providers established similar data centres and possibilities of data access as well. Company registers and broad data access—for example, in Sweden—allowed even more sophisticated and detailed analyses that were able to address completely new research questions (see, for example, Jung and Ejermo 2014).

All these developments were possible because of the step change in technological progress of computing power and software packages. Local servers instead of super-computers in the computing centres of—mostly only—selected universities were able to handle the relational databases in a satisfactory manner. Even desktops and laptops gained the computing power to analyse the extracted data or acted as access points to the central servers of the innovation and economics institutes that were working on these topics.

In consequence, the number of institutes using innovation data especially universities worldwide and the number of authors analysing or even developing new innovation indicators grew very quickly since the middle of the first decade of the 2000s. This is visible in the number of publications using the keywords patent, publication or bibliometrics in their title (Fig. 2)

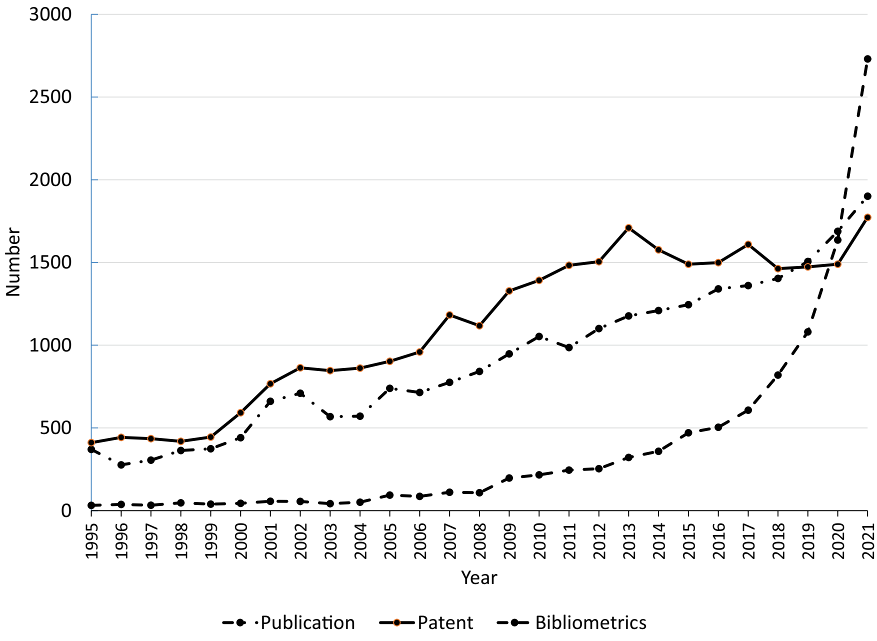

Fig. 2 Number of publications on patents, publications and bibliometrics. Source: Elsevier - Scopus; own representation

6 Summarising Conclusions: Historical Developments and Challenges of the Near Future

In this chapter, we outline and interpret the evolution and development of innovation indicators since the early 1970s. We identify four driving factors of innovation indicators provision and use, namely (1) new theories/concepts, (2) lower technical thresholds for data analyses and availability of new data, (3) increasing policy demands and (4) technological and economic developments, mainly the shift towards R&D-intensive sectors and technologies. Our discussion shows that at different stages of the indicator development different factors are the driving forces.

While in Schumpeter's time the focus was on the individual entrepreneur and his/her impact on technological progress and innovations, the post-Second World War era was characterised by a change in the innovation processes and their organisation, based on a division of labour and responsibilities. This led to a need for innovation indicators that are internationally comparable and generally applicable. In addition, the first innovation-oriented political programmes and the first innovation indicators appeared about 1990.

In this first phase of a broadening take-up of indicators in the 1960s and 1970s, various scientific entities at different universities and research institutes emerged—among them Fraunhofer ISI in 1972—that took innovations and innovation processes, as well as science and innovation policy as their subject of analysis. Individuals in these organisations pushed the conceptual and methodological foundations further ahead (driving factor 1 of our model). New disciplines, namely innovation economics, STI policy analysis and STI indicators were born. Ever since, innovation indicators and innovation policy (factor 3) have been closely intertwined and have led to evidence-based policy-making (see, for example, Dosso et al. 2018).

> Indicators (are) the instrument of an ambitious and open S&T policymaking: Indicators feed analysis and argumentation by opening the black box of the scientific community and of the political decision (Arvantis et al. 1986).

The early innovation indicators were primarily linked to the OECD and outstanding monitoring and standardisation efforts, the establishment of the Science Citation Index (now Web of Science), the engagement of national bodies such as the US National Science Foundation and more recently international bodies such as the ILO or World Bank. Innovation indicators were mainly R&D-centred with a strong focus on the manufacturing industry and R&D processes in companies as well as the science systems. The origin and target of these analyses were the monitoring and performance measure of science systems that then shifted towards the competitiveness of nations. Essentially, next to case studies and survey data, the majority of indicators were of macro-economic nature, addressing national or technological levels. The innovation system's perspective widened the focus on various actors and their interplay, which also led to the introduction of additional indicators, among them indicators on transfer and collaboration (factors 1 and 4). Data availability and better options for data treatment and analysis (factor 2) gave the indicators

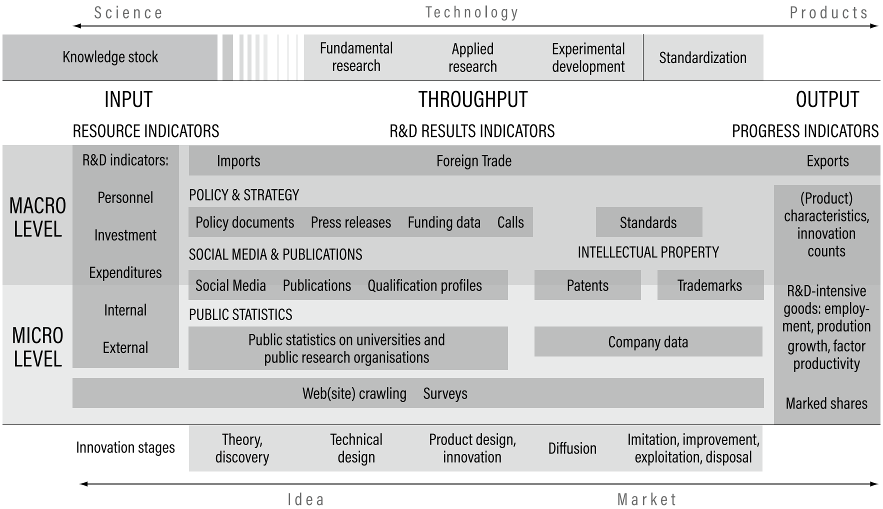

Fig. 3 Schematic representation of indicators in the innovation process. Source: own representation based on Grupp (1998) and Frietsch and Jung (2009)

development another push since about the year 2000. More recently, information and computer science methods have entered the innovation indicators scene and widened the scope even further. These latter developments supported a shift away from the macro-level to more micro-level and process-oriented indicators and analyses. Surveys are no longer the only option for micro-analyses, but company databases and their matchings with other data sources offer—in most cases even a more large-scale—option for analysing companies, research organisations, projects or even individuals. The use of unstructured (text) data is about to push the possibilities even further. More differentiated information, qualitative aspects and completely new insights might be introduced into STI analyses, based on large language models.

A schematic representation of (a selected set of) innovation indicators is depicted in Fig. 3. It tries to grasp the admittedly simplifying logic of the linear model (Bush 1945; Godin 2003) of innovation when it orders the indicators from left to right along the dimension of input, throughput and output. More conceptually, the scheme sketches the continuums from science to technology (see top) or from idea to the market (see bottom). A differentiation of the indicators that rather address the macro-level and those that rather address the micro-level is also represented. The figure shows the larger and further growing landscape of innovation indicators. Traditional indicators like R&D expenditures, patents, publications, trade or production data are supplemented by trademarks, standards, company data or unstructured data sources like web-crawling.

Among the major new trends in innovation, which will have an impact on the conception of indicators, is a further increasing relevance of science-based technologies such as batteries, fuel cells, nanotechnology, quantum technologies, materials, or maybe also fusion power technologies (factor 4). A further phenomenon is the steadily increasing number of new services and (digital) business models. Among the current challenges of innovation research as well as innovation indicators might be a shift in the relevance of manufacturing companies towards a few enterprises from the IT sector such as Apple, Google, Microsoft, Huawei, Amazon, Facebook, etc. For a more detailed assessment of technologies, a combined analysis of many different indicators such as patents, publications, enterprise structure, foreign trade, price structure, international linkages production structures, supply chains, sustainability, impact on climate change, etc. will gain more relevance. New concepts and perspectives like the question of Technology Sovereignty (Edler et al. 2020, 2023) demand new indicators or interpret established indicators differently. The available indicators conceived in the last 50 years are a good basis for analysing the development of innovation in the next years. What stays constant is a steady effort to conceive new indicators. Adapting them to new phenomena is a great challenge.

However, we should not forget that indicators are a means to measure and assess constructs which are otherwise not directly measurable. They should not become a means in itself. Recently there has been some fundamental critique on the current status of indicators. While Goodhart's law is a fundamental critique of any indicator becoming a means in itself, some more specific criticisms (e.g. Larivière and Sugimoto 2019; Moed 2018) have been raised with respect to S&T indicators. For example, Barré (2019, p. 44) sees a "landslide of instrumentalised S&T indicators" since the mid-90s to the present day. In this context, he mentions the link between new public management and bibliometrics and linked to that publication statistics as tools for competition, the increased funding of scientific research by enterprises and the emergence of an industry of science information. Barré complains that "the indicator is integrated in the social, professional and cultural norms and has become the undisputable reality of the object or phenomenon. It is forgotten that an indicator is only a proxy, but not the object". In this context, he speaks about "culturally produced ignorance". However, many researchers struggle to correct these misleading activities, e.g., the San Francisco Declaration on Research Assessment-DORA (ASCB 2012), the Leiden Manifesto (Hicks et al. 2015) or the review of the use of metrics in the UK research assessment (Wilsdon 2015).

It seems that many options, but also challenges stay ahead of indicator-based science and innovation research. This makes this field so attractive to many young researchers, who will push the frontiers even further. Artificial intelligence based on large language models already opens a new avenue of research that might be able to simplify and differentiate classification tasks that were a bottleneck for many decades. Neural networks will help to detect relations of topics, organisations or persons, helping to better understand the relations, effects, causalities and impacts of certain factors in the science and innovation systems. New questions will arise and new answers will be given. The new possibilities, even after more than 50 years of indicator development, still let it appear a rather young and dynamic field.

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