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Theme issue contribution

From Research Evaluation to Research Analytics. The digitization of academic performance measurement

Anne K. Krüger and Sabrina Petersohn

Abstract

One could think that bibliometric measurement of academic performance has always been digital since the computer-assisted invention of the Science Citation Index. Yet, since the 2000s, the digitization of bibliometric infrastructure has accelerated at a rapid pace. Citation databases are indexing an increasing variety of publication types. Altmetric data aggregators are producing data on the reception of research outcomes. Machine-readable persistent identifiers are created to unambiguously identify researchers, research organizations, and research objects; and evaluative software tools and current research information systems are constantly enlarging their functionalities to make use of these data and extract meaning from them. In this article, we analyse how these developments in evaluative bibliometrics have contributed to an extension of indicator-based research evaluation towards data-driven research analytics. Drawing on empirical material from blogs and websites as well as from research and policy papers, we discuss how interoperability, scalability, and flexibility as material specificities of digital infrastructures generate new ways of data production and their assessment, which affect the possibilities of how academic performance can be understood and (e)valuated.

Keywords: Infrastructure studies; data analytics; evaluative bibliometrics; academic performance measurement

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Introduction

With the promise of "using advanced data analytics and super-computer technology" for processing "large amounts of data to generate powerful analyses and visualizations on demand" (Elsevier 2021a) by Elsevier's software program SciVal, academic performance measurement seems to have entered a "brave new world" of research evaluation. Yet, one could say that bibliometric measurement of academic performance has always been digital. Since the launch of the first citation database, the Science Citation Index (SCI), in 1964, bibliometrics has been tied to computer-based citation databases.[1] The SCI was based – though still with punch cards – on the use of newly developed IBM computers to compile scientific literature based on indexing citations (Wouters 1999). So what is new about digitized valuation in academic performance measurement?

Since the 1970s, citation databases have hugely broadened their range of functionality, content, and coverage and developed into an expansive digital infrastructure. What had been conceived of initially as a new method of information retrieval has evolved into a predominant tool for research evaluation (Garfield 1964; de Rijcke and Rushforth 2015; Petersohn and Heinze 2018). The digitization of academic performance measurement has since then accelerated at a rapid pace. Technological developments such as greatly increased storage and computing capacities as well as advanced data harvesting and assessment techniques have opened up an abundance of new data sources such as books and funding acknowledgements but also downloads, twitter mentions and likes, the latter coined "altmetrics" (Franzen 2015; Haustein et al. 2016). This datafication (Boyd and Crawford 2012; Mayer-Schönberger and Cukier 2013) of academic publishing and evaluation has triggered an unforeseen dynamic of expansion and diversification in bibliometric infrastructure for academic performance measurement.

In this article, we analyse the development of digital infrastructure in evaluative bibliometrics which has contributed to an extension of indicator-based research evaluation towards data-driven research analytics. With our case of bibliometric infrastructure, we aim to contribute to the study of digitized valuation by highlighting how the material specificities of digital infrastructures influence the production and assessment of data in valuation processes. In a first step, drawing on comprehensive empirical material from blogs and websites from data providers, funders, and companies as well as on research and policy papers, we demonstrate how bibliometric infrastructure, including not only citation databases but also persistent identifiers,

[1] Godin has shown that there have also been analogue "forerunners to bibliometrics" (Godin 2006: 109) at the beginning of the 19th century when psychologists started collecting information about their disciplinary output of publications.

altmetric data aggregators, software tools, and information systems enable new modes of data production and assessment based on their distinct features of interoperability, scalability, and flexibility (Tilson et al. 2010; Büchner 2018). In a second step, we discuss how this development unfolds a "generative potential" (Mennicken and Kornberger 2021: 464) extending indicator-based research evaluation towards data-driven research analytics, influencing the possibilities of how academic performance can be understood and (e)valuated.

A short introduction to evaluative bibliometrics

Bibliometrics, the scientific discipline at the intersection of library and information science, sociology, history of science, and science policy, revolves around the application of mathematics and statistical methods to measure scholarly communication and to generate insights into the growth, structure, and development of scientific fields (Pritchard 1969; Debackere et al. 2019). Already in its formative years and fostered by the growing interest of the nascent science policy community in the 1960s and 1970s, the sub-field of evaluative bibliometrics (Narin 1976) branched out, providing methods, tools, and techniques for the quantitative measurement of academic performance in terms of its impact and output (Furner 2014; Debackere et al. 2019). After an experimental phase in the 1970s and 1980s, the use of bibliometrics in science policy and research management became a consolidated, yet continuously disputed practice in the 1990s. It nevertheless proliferated in performance-based funding schemes in national research assessment (Hicks 2012) and institutional resource allocation models (Hammarfelt et al. 2016) down to the use of individual-level metrics for getting hired or tenured, showcasing achievements and self-monitoring impact as well as obtaining funding (Nicholas et al. 2020). Furthermore, the 2000s saw the advent of university rankings as global benchmarking tools that were and still are building on citation databases (Hazelkorn 2011; van Raan 2019). Additionally, by this time, the use of evaluative bibliometrics had become institutionalized and among some stakeholders, such as research administrators, an (even too) popular practice (Gingras 2016).

These practices of quantified research evaluation rely heavily on bibliometric indicators such as the h-index or highly cited publications which have become an integral part of researchers' CVs (Nicholas et al. 2020) or on the use of publication counts and other aggregate output measures as witnessed, for instance, in the Australian performance-based research funding formula (Butler 2003). This indicator-based research evaluation generates insights into academic performance that is supposed to complement (Moed 2007; Derrick and Pavone 2013) or is feared to supplant or override judgement by academic peers, thereby moving evaluation "from a skilled operation to an automated, mechanical one" (Gingras 2016: 57).

This concern of automated analysis, however, was exacerbated by developments at the turn of the century. With the rise of the internet and subsequent digitization of academic publishing the idea of measuring scholarly impact online through webometric methods such as content analyses of web pages or hyperlink counts started to gain traction (Thelwall et al. 2006). Growing criticism regarding the narrow conception of scholarly impact as well as the growth of social media platforms spurred the development of altmetrics in 2010 (Björneborn and Ingwersen 2001; Priem 2014; Nuredini et al. 2021).[2] With the development of altmetrics and respective tools to generate them, a conceptual shift took place from the closed universe of citation databases towards a myriad of different data types such as clicks, downloads, views, tweets, mentions, or likes that were attributed relevance for indicating research performance. Yet, these data did not only extend the database for bibliometric analyses of research performance; they furthermore turned the idea of indicator-based research evaluation as measuring scientific merit *within* academia towards including research impact upon society at large.

The rise of altmetrics demonstrates two things: First, it shows that the digitization of academic publishing and communication has enabled new modes of data production for evaluative purposes. Second, it highlights how technical developments in bibliometric infrastructure can influence our understanding of what academic performance is about. While research on evaluative bibliometrics has been strongly centred on methodological questions of database coverage and quality, indicator construction, their usage, and consequences (de Rijcke et al. 2016; Moed 2017),[3] we therefore contend that the story of evaluative bibliometrics should not be told with a focus on common and alternative indicators for academic performance alone. Instead, research on academic performance measurement should also take into account the constantly progressing development of digital infrastructure that provides unprecedented data sources and respective tools to produce, process, and assess data. Focusing on the digitized bibliometric infrastructure behind academic evaluation, we ask how its constant growth affects the possibilities for academic performance measurement. We suggest that the ongoing

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[2] Altmetrics comprises many different types of "online metrics that measure scholarly impact" (Haustein 2016: 415) which are generated on social networking platforms such as Facebook and ResearchGate, reference managers like Zotero and Mendeley, microblogging sites such as Twitter and social data sharing on Figshare or Github (Haustein 2016: 415).

[3] See for an exception Aström (2016) who has started theorizing on the relation between digital infrastructure, indicators, and evaluation practices in bibliometrics.

development of digital infrastructure gradually extends evaluative practices from indicator-based evaluation towards data-driven research analytics. The evaluation of scientific practice no longer depends on predefined indicators alone. Instead, constantly expanding possibilities in data production and assessment are becoming the drivers for how academic evaluation can be practised raising questions about the influence of data-driven analytics on the understanding and valuation of scientific practice as such.

Digital infrastructures in valuation processes

By 1995, Theodore Porter had already concluded that processes such as the production of seemingly objective performance measurement through quantification are influenced by technology: "Once the numbers are in hand, results can often be generated by mechanical methods. Nowadays this is usually done by computers" (Porter 1995: 6). This quote shows that Porter still thought of computers as assistance to quantitative evaluations. However, today, they have come to play a crucial role not only in data assessment, but furthermore in data production through automated processes extending the amounts of assessable data to unprecedented quantities. The assessment of data through automated tools (Amoore and Piotukh 2015) and, moreover, the digitized production and processing of data about social practices and individual characteristics have become a crucial feature in current valuation processes (Lupton 2016; Fourcade and Healy 2017; Kiviat 2019). The availability of technologies is constantly generating more ways of how data can be easily produced and assessed for various kinds of evaluative practices.

The production and assessment of data through digital infrastructures have already been discussed in a considerable number of studies. Already in the 1990s, Bowker, Star and Ruhleder had addressed the question of how computer-based information systems were set up to produce data to support working routines based on predefined classificatory systems (Star and Ruhleder 1996; Bowker and Star 1999). Studying the introduction of computer-assisted administration to nursing care in hospitals, Bowker and Star demonstrated the performative effect of such infrastructure, intending to categorize the full range of nursing practices. While this infrastructure makes visible and acknowledges the multiple requirements of patient care that nurses constantly accomplish, it also defines how such work has to be done, allows for controlling employees, and makes other practices that are not captured within these categories become invisible (see also Star and Strauss 1999). Digital infrastructures thus perform a specific understanding of the processes they are supposed to support. Their performativity is based on inscribed meanings and accounts of worth that their developers and providers and often even their users take for granted.

The socio-material performativity of digital infrastructures has become a crucial aspect for studying the development and implementation of software systems for administrating and evaluating work processes in organizations. Yet, we also contend that the research perspective on performativity might need to be extended due to the increasing digitization of various processes and practices of everyday life jointly with the enormous growth of computing capabilities. While much research has focused on the socio-material assemblage of technology and social practice, particularly focusing on the *social practices* of either the providers or the users of technology and technology's performative effects on their practices (Pollock and Williams 2007, Orlikowski and Scott 2008; Wagner et al. 2011; Bowker et al. 2019), it has become necessary to ask for the "generative potential" (Mennicken and Kornberger 2021: 464) of digital infrastructures. They do not only *assist* social practices of data production and assessment, but instead *generate* themselves new objects and structures in terms of unprecedented quantities of datasets and linkages between them triggering new ways of assessing them.

In his study on the introduction of the stock ticker in financial markets, Preda addresses the stock ticker technology as a "generator" of new temporal structures in financial market practices (Preda 2006: 754). The stock ticker was able to constantly present data on prices making any variation in prices immediately visible. Preda finds that this material specificity of immediate price data visualization led to a restructuring of representational language, cognitive tools and categories, and group boundaries. He moreover argues that this new technology of data production and presentation dramatically changed how financial markets were enacted. Stock ticker technology made time become a crucial factor in "playing the investing game" (Preda 2006: 768). Alaimo and Kallinikos also argue for the generative capabilities of technology. Studying the recommender system of the audio streaming platform Last.fm, they discuss how automated technologies "blur the distinction between humans and machines" (Alaimo and Kallinikos 2021: 18) within organizations. Key operations in organizations are becoming performed by technology instead of human experts. Contrary to Bowker, Ruhleder and Star and their studies on the inscription of predefined classificatory systems into technology, they highlight that recommender systems do not build on predefined music genres, but instead construct new music categories by producing data about songs and their listeners focusing on relations between them (see also Unternährer 2021).

These studies altogether highlight the generative potential of technology due to its *material specificities* that do not only perform an effect on practices through inscribed and predefined classificatory systems. They also generate new ways of creating, categorizing, and thus structuring objects based on their technical capabilities of producing linked data. Studying the development of bibliometric infrastructure in academic evaluation makes it necessary to ask not only for normative classifications and accounts of worth about academic "performance", "output", and "impact" that are inscribed into technology. But also, to understand how the constantly progressing digitization of bibliometric infrastructure is changing how academic evaluation can be realized, we need to focus on the material specificities that are created through digitization and respective technological developments.

The material specificities of digital infrastructures have already been addressed in information systems research. Tilson et al. define digital infrastructures – particularly in contrast to physical infrastructures – "as shared, unbounded, heterogeneous, open, and evolving sociotechnical systems comprising an installed base of diverse information technology capabilities and their user, operations, and design communities". They emphasize that such infrastructures "cannot be defined through a distinct set of functions [...], or strict boundaries [...]. In contrast, they are characterized by dynamism and longevity and are relational in nature" (Tilson et al. 2010: 1–2). Digital infrastructures per se are not static and predetermined in their usages and meanings. Instead, their material specificities can be characterized through three distinct features (see also Büchner 2018): Digital infrastructures can be made *interoperable* with other tools and devices depending on their application programming interface (API). This interoperability enables more and diverse uses of the same data through connecting new devices and allowing for mutual data exchange. Yet, it also allows for interconnecting multiple sets of different data and analysing the relations between them. Digital infrastructures are also *scalable*. They can be easily reduced or enlarged and new modules with new functionalities can be constantly added to an already existing system. This scalability leads to the capability to constantly produce and process various kinds of data and metadata which makes digital infrastructures highly *flexible* in their application because the meaning of these data is not predefined. Instead, data is made meaningful through the inscribed functionalities of the infrastructures and how they are put into use. Digital infrastructures thus do not produce data that can only be used in a particular context.

The interoperability, scalability, and flexibility of digital infrastructures enable the aggregation and linkage of masses of data and allow for a constant search for new ways to extract meaning from them. These material specificities make the production and assessment of data an intrinsic characteristic of digital infrastructures. Which kinds of data can be produced, how these data can be linked, and, finally, how they can be processed and meaningfully assessed is not structured through the social inscription of categories and classifications alone. It also depends on material constraints and affordances provided by technology. Yet, we do not claim that such specificities necessarily lead to specific practices.[4] Instead, we argue that we should take the role of technology seriously in its generative potential to determine what counts as meaningful and valuable.

In our case study on current developments in evaluative bibliometrics, we trace the increasing interoperability, scalability, and flexibility of bibliometric infrastructure to shed light on how these features have enabled new ways of producing, aggregating, and linking data about scientific practice generating new possibilities for academic evaluation. We focus on specific parts of this digital infrastructure namely citation databases, altmetric data aggregators, and persistent identifiers as well as software tools and current research information systems. We discuss how they enable and promote a constantly progressing extension from indicator-based research evaluation towards data-driven research analytics that might change the understanding and valuation of scientific practice as such.

From citation indices to linked data: Charting the development of bibliometric infrastructure

Our analysis of the development and material specificities of central citation databases – the most influential altmetric data aggregators, mature persistent identifiers as well as widely spread software tools and current research information systems as crucial parts of bibliometric infrastructure – rests on a broad range of empirical material. We have searched websites from companies, foundations, and other organizations dealing with bibliometrics, research policy, and data analytics. Additionally, we have studied blogs,[5] the GitHub repository, research publications on bibliometric methods, indicators, tools, and databases, as well as grey literature such as policy documents or white papers to chart the growing landscape of bibliometric infrastructure. In our data collection and analysis, we have focused on developments from the year 2000 onwards when the databases Scopus and Google Scholar emerged as first competitors to the long-lasting monopoly of Web of Science as the only provider of citation data transforming bibliometric infrastructure into “a crowded marketplace” (de Rijcke and Rushforth 2015).

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[4] See for arguments against technological determinism MacKenzie and Wajcman (1999).

[5] These blogs comprise, in particular, the Bibliomagician and Leiden Madtrics as well as blogs from Crossref, ORCiD, and ROR.

Citation databases

The fundamental backbone of bibliometric infrastructure consists of citation databases that collect and store data and metadata about publications, their authors, and citations (see Figure 1). In 1992, the original Science Citation Index was acquired from its inventor Eugene Garfield and his Institute of Scientific Information by the information company Thomson Reuters and renamed Web of Science. Web of Science has broadened its coverage and selection policy beyond the initial focus on journal articles and also added conference proceedings, books, and data over the years (Birkle et al. 2020), thereby extending its content towards applied sciences, arts and humanities as well as social sciences. The ownership of the citation database changed again in 2016 when the company Clarivate acquired Web of Science. Web of Science is accessible to subscribers by a web interface for basic searches and for referring to the Journal Impact Factor, h-index and other citation metrics. APIs allow "power users" in research management to apply more advanced searches and analyses (Birkle et al. 2020). It currently covers up to 155 million records of publications (Martín-Martín et al. 2021).

For more than 40 years, Web of Science has remained the one and only citation index available. Its monopolistic position was challenged in 2004 by the international publisher Elsevier which launched its curated, selective citation database Scopus. Scopus contains at least 76 million records (Martín-Martín et al. 2021) and has become an equally important resource for bibliometric large-scale analyses and policy purposes such as national and institutional research assessments, governmental policy analyses and reports as well as university rankings (Baas et al. 2020). Like Web of Science, it incorporates citation and journal metrics, some of them especially developed based on Scopus data, like the CiteScore (Teixeira da Silva and Memon 2017). APIs provide limited or full access to citation records, search functionalities, and download options depending on the subscription model chosen (Baas et al. 2020).

Shortly after the introduction of Scopus, Google Scholar was launched by big tech giant Google. Google Scholar differs significantly from the traditional citation databases. Contrary to Web of Science and Scopus, it does not only provide free access to its database with a simple, easily accessible and usable web interface. Google Scholar also indexes online available research documents of any kind of quality, form, and type, regardless of whether the content is peer-reviewed or not or even published in a journal. It represents the first academic web engine of its kind (Orduña-Malea et al. 2014). Instead of offering curated content following the principle of selectivity, Google Scholar applies an unsupervised indexing process based on automated bots crawling the web. Citation counts can only be provided based on the extraction of cited references from retrieved full texts which impacts not only data quality but also the computation of respective citation metrics (López-Cózar et al. 2019). Although no official figures exist, it is estimated that it contains more than 300 million records (Martín-Martín et al. 2021).

Another free citation database that also functions like an academic search engine based on Bing's web crawling infrastructure was Microsoft Academic Search, which was developed in 2006 by Microsoft in response to Google Scholar. The database developed at a rapid pace: being limited at first to computer science and technology fields, it expanded to more subject categories based on agreements with different source providers and improved technical features such as browsing capabilities. Similar to the aforementioned databases, Microsoft Academic Search also contained bibliometric performance indicators as well as visualizations of publication, citation and authorship networks (Orduña-Malea et al. 2014). While this version was silently obsoleted in 2012, Microsoft opted for a relaunch in 2016 with a new design and motivation. Cloud-computing and artificial intelligence technologies formed the technological backbone of Microsoft Academic and of its core component, the Microsoft Academic Graph. The graph was a network-like structure comprising bibliographic metadata and the relationships among them (Wang et al. 2020). By means of machine reading and artificial intelligence all Bing-indexed webpages, metadata feeds, and publishers were text-mined and organized into the graph (Microsoft 2021b). The Microsoft Academic Graph covered around 255 million records from all stages of research publications, ranging from preprints to reprints (Orduña-Malea et al. 2014; Wang et al. 2020). Via an API data could be retrieved either as raw data or as pre-processed data (Hug et al. 2017). However, Microsoft Academic was discontinued in 2021 (Microsoft 2021a). Non-profit initiatives such as the database OpenAlex have stepped into this void, using data from the Microsoft Academic Graph and combining it with more data gathered from other sources and web crawls. It was launched in spring 2022 by OurResearch (OpenAlex 2022).

Besides OpenAlex the most recent addition to the database backbone of bibliometric infrastructure is Dimensions by Digital Science, which was launched in 2018. This database differs significantly from the others because it is not a strictly bibliographical database but also contains a wider set of document types such as awarded grants, policy papers, clinical trials and patents next to scholarly publications and their citations. It sources data from a variety of organizations, indices, and initiatives. The proclaimed ambition of Dimensions is to broaden the narrow frame of publication and citation analyses (Herzog et al. 2020). The database now amounts to over 105 million records (Martín-Martín et al. 2021). Dimensions aims for "not only aggregating millions of previously siloed records but also creating links between these records based on increasing occurrence of persistent identifiers, as well as AI-based techniques, and by mining relationships referred to in full text" (Herzog et al. 2020: 390). It thus enables the linkage of different datasets providing encompassing metadata about publications, their authors, their funding, and resulting "output" such as patents, clinical trials, or policy references. The developers refrain from creating their own metrics and indicators as do Web of Science, Scopus and Google Scholar, or from providing data for university rankings. However, Dimensions actively encourages large-scale bibliometric analyses including indicator development by the scientometric research community via a dedicated API for data retrieval and analysis (Herzog et al. 2020: 390). Dimensions is accessible in its free version from online interfaces that allow for contextual search and data visualizations for research purposes. Institutional reporting and analyses or consulting are, however, only possible based on subscriptions (Herzog et al. 2020: 390).

Although differing in their coverage and selection policies, these citation databases have grown by millions of records since their inception. The increasing data volume allows for flexibly deriving citations from increasingly varied sources and publication types as well as other forms of output such as patents or policy papers. While most of these databases incorporate and effectively disseminate their own set of metrics and indicators (Jappe 2020), developments such as the Microsoft Academic Graph, OpenAlex or Dimensions' approach of "linked research data from idea to impact" (Dimensions 2021a) demonstrate that networked graphs become increasingly important extending indicator-based research evaluation towards research analytics. Instead of predefined indicators, such ways of producing, linking, and presenting masses of data display correlations that provide the ground for "discovery and analytics" (Dimensions 2021a) without any pre-given operationalization of what academic performance is about. While the providers of OpenAlex and Dimensions promote the scientific use of their linked data, fee-based licence models also exist for commercial and large-scale purposes. With these licence models, database providers also foster research analytics' entrance into the market for data-driven research intelligence.

Besides the linkage of different datasets, all of these citation databases display a high amount of interoperability and scalability. As we highlight in the following sections, they incorporate persistent identifiers to enhance data quality and also offer APIs for data retrieval and analysis. These interfaces allow for their integration in software tools and current research information systems that provide meaning to these masses of linked data on research and researchers.

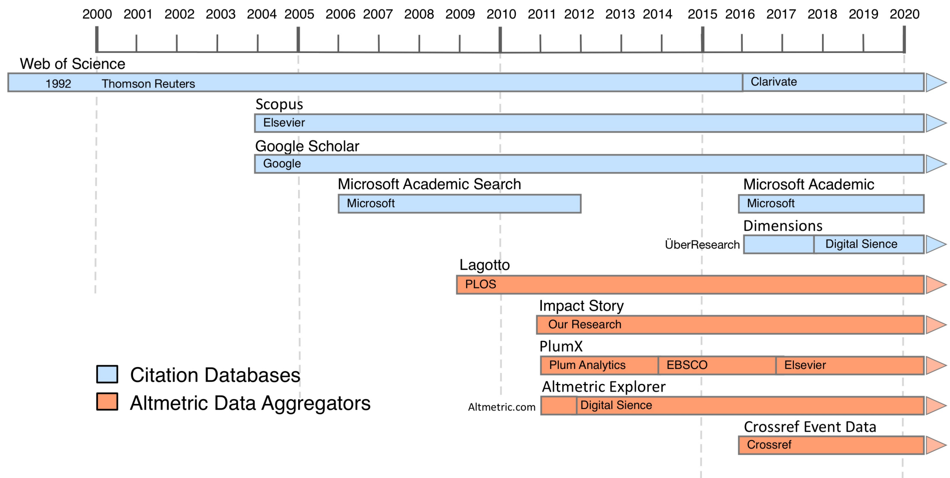

Figure 1. Development of citation databases and altmetric data aggregators.
Source: Authors' own illustration.

Altmetric Data Aggregators

With the digitization of academic publishing, it has not only become easier to collect data about publications, authorship, and citations. Also, the communication behaviour of researchers including "publishing, posting, blogging, scanning, reading, downloading, glossing, linking, citing, recommending, acknowledging" (Cronin 2005: 196; cited in Haustein et al. 2015) has turned into a new source for tracking the usage of research publications. Since then, new ways of producing data on research usage have been established. So called altmetric data aggregators[6] collect data resulting from views, downloads, blog posts, tweets and other digitally visible forms of usage based on sources such as bibliographic reference managers, social media platforms or even policy documents and make them publicly available (see Figure 1). While it takes some time for publications to become cited, these data are propagated as measuring research impact in real-time by the scientific community and even society at large (Priem et al. 2010).

The Public Library of Science (PLOS) became the first database to produce data about the online usage of research articles. In 2009, they started the open source application Lagotto to provide data based not only on their own counts of views and downloads (Lagotto n.d. a) but also on other external sources such as the bibliographic reference manager Mendeley, the social media platform Twitter, and Crossref.

[6] See for a comprehensive comparison of different aggregators Zahedi and Costas (2018) and Ortega (2020).

They classified these data into the categories "viewed, saved, discussed, recommended, and cited" (Lagotto n.d. b) as these categories were intended to represent different forms of user engagement and thus of impact (Lin and Fenner 2013).

These first developments were followed by the "altmetrics manifesto" from Jason Priem and colleagues in 2010 which called for enlargement of the focus of measuring research impact beyond the often problematic citation counts for better giving credit to researchers and their impact (Priem et al. 2010). In 2011, jointly with Heather Piwowar, Priem founded the non-profit organization ImpactStory.[7] ImpactStory is an online platform where researchers can create a profile including different kinds of their research output like publications and pre-prints as well as datasets and software. Based on a software tool called "total-impact" Priem and Piwowar claim to be able to "capture unprecedented amounts of data showing all sorts of uses of all sorts of products by all sorts of people" (Priem and Piwowar 2012). ImpactStory provides researchers but also other users such as funders with information about the usage of these research items including various sorts of mentions in academic contexts, the geographical reach of their research, or their open access activities. Priem and Piwowar highlight that ImpactStory does not only provide its users with numbers but also puts these numbers in context by comparing them with achievements of other researchers (Priem and Piwowar 2012). In addition, ImpactStory allows for the reuse of its data providing a free API.

ImpactStory, however, is not the only online platform that aggregates different sorts of data on the usage of research. In the same year, two further altmetric data aggregators were launched based on a similar idea. Altmetric.com displays article-level metrics as a colourful "altmetric donut" with each colour highlighting a different kind of source where an article has been mentioned. It furthermore provides the *Altmetric Attention Score*, which is "an automatically calculated, weighted count of all of the attention a research output has received" (Altmetric n.d. a). Like ImpactStory, Altmetric.com equally addresses not only researchers but also publishers, research organizations, and funders. In 2012, the start-up became part of the Digital Science portfolio (Wikipedia 2021a). Altmetric.com provides a free API for scientometric research, but access can also be purchased by commercial users (Altmetric n.d. b).

Another altmetric data aggregator has been developed by the company Plum Analytics. With their tool PlumX, they provide altmetrics for a broad variety of research objects (Herb 2019). PlumX is thus neither focused on the individual researcher nor on research

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[7] Today, the organization has been renamed OurResearch, with ImpactStory as one of their products.

publications. Nonetheless, it can be used to track the altmetrics of individual research output. Since 2015, with the PlumX suite, it has also included a benchmarking tool for research organizations (Wikipedia 2021b). Unlike ImpactStory, it has no freely accessible API. Instead, since it was acquired by Elsevier in 2017, which now uses PlumX across their journals to display the metrics of research articles, it is open only to Scopus subscribers (Scopus 2019). However, its metrics are publicly accessible.

A more recent development is Crossref Event Data, which started in 2016. The term "event data" refers to a similar kind of data deployed by other altmetric data aggregators such as a mention in a blog post or a comment on a social media platform. Contrary to Altmetric.com and PlumX, Crossref Event Data neither offers website plugins nor provides metrics or any other sort of data analysis. Instead, Crossref allows access through an open API highlighting that they only "provide the unprocessed data – you decide how to use it" (Crossref 2020a). They explicitly refrain from presupposing distinct uses of their metadata. Yet, they regard "data intelligence and analysis organisations" (Crossref 2020a) among their potential users.

These different altmetric data aggregators have in common that they seek to complement or even to outstrip traditional citation indices as the primary source of information about academic performance fostering data exchange and interoperability with citation databases and other software tools for research assessment by providing APIs. They flexibly build on the rapidly changing digital traces of research items and any kind of online interaction with them to generate meaning about impact within and beyond academia. To this end, they create new metrics and indicators such as the *Altmetric Attention Score* or *ImpactStory achievements*. However, these efforts to establish digital traces as meaningful indicators have also become ends in themselves[8] leading to a "lack of a theoretical foundation coupled with (…) pure data-drivenness" (Haustein 2016: 418). Altmetrics are thus not based on methodologically sound operationalization defining what they can or cannot indicate. Instead, their production is determined by technical affordances and commercial interests leaving open the question as to how these data can actually be interpreted and used for evaluation purposes. Indicators are thus not only the basis for research evaluation but themselves a product of data-driven analytics.

Persistent identifiers

Persistent identifiers are digital markers that were developed to unambiguously identify researchers, research organizations, and

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[8] Additionally, academic social networking sites like ResearchGate and Academia.edu use data analytics to predict and foster social interactions among members attempting to identify future research trends (Delfanti 2021).

research objects (see Figure 2). The idea followed from the constant digitization of academic publishing and the growing digital storage of research output such as publications but also datasets, software, and other research objects. Persistent identifiers were invented from the 1990s onwards to address challenges resulting from the problem, also known as "link rot" (Klump et al. 2017: 1), where internet references did not permanently link an object to a persistent URL; URLs could change making the linked object inaccessible and irretrievable (Dellavalle et al. 2003). It was feared that research output might get lost if there was not a reference system for online publications and other digital research objects reaching beyond the unstable web links.

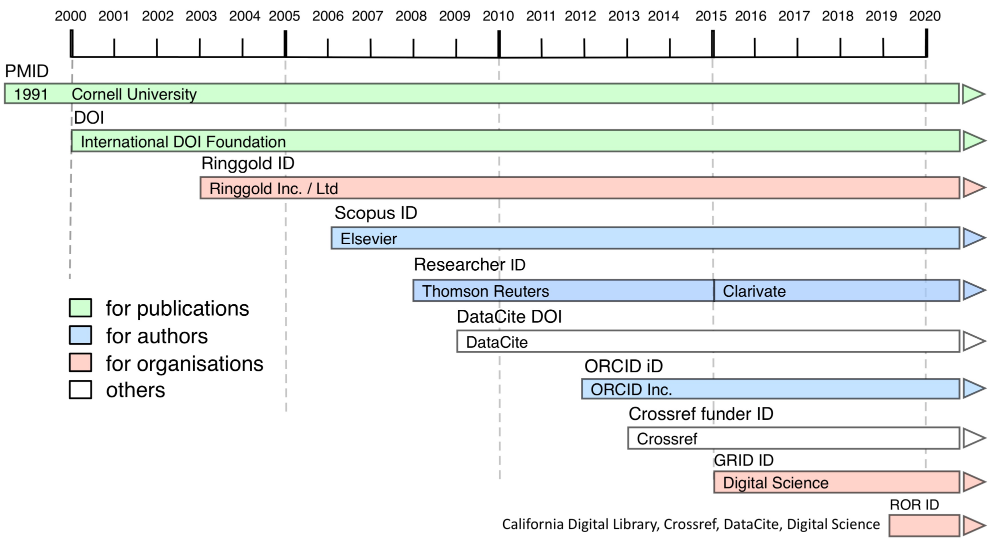

Figure 2. PID development.
Source: Authors' own illustration.

The PubMed ID (PMID) and the Digital Object Identifier (DOI) became the most prominent ones for research publications with the DOI as the only persistent identifier that is currently used by academic journals across publishers and disciplines. The DOI consists of letters and numbers that provide a unique and unambiguously identifiable signature for a particular research publication. It also provides metadata such as the author and the place where a research article is published that become inextricably linked to the article. The DOI has thus become the core technology for the digital academic publishing system allowing for the unambiguous identification and correct referencing of a publication and the constant monitoring of its output (Paskin 2010). In 1997, the International DOI Foundation (IDF) was established, which to date manages the assignment of DOIs to research publications (International DOI Foundation 2015).

The DOI gained traction particularly through the foundation of Crossref (before CrossRef) in 2000 (Crossref 2020b). Crossref was founded as an initiative of influential publishers who saw a need to adapt to the age of digital publishing. They started to provide links between articles and their references across journals of different publishers that were only possible based on the accurate identification of publications using the DOI as their key signature (Meadows et al. 2019: 3). The unambiguous identification of research publications facilitated the tracking of citations in other publications. To date, the IDF has assigned approximately 257 million DOIs to digitally as well as physically available objects through several registration agencies (International DOI Foundation 2021).

Besides institutionalization of the DOI as a standard marker for research publications, there are constant new attempts to broaden its scope or even to establish further persistent identifiers. While the DOI was originally designed for identifying research publications, organizations such as DataCite, which was founded in 2009, are attempting to enlarge the scope of the DOI towards further research objects such as research datasets. Crossref has moreover started to build a persistent identifier for funding bodies. They promote these efforts with the idea of having "transparency into research funding and its outcomes" (Crossref 2020c). Currently, there are, in particular, two further persistent identifiers which are pushed to the fore: the Open Researcher and Contributer ID (ORCID) for researchers and the Research Organization Registry (ROR) for research organizations.

The ORCID iD is designed as a persistent identifier for researchers. It was launched in 2012 and is operated by the non-profit organization ORCID Inc. It was founded by major publishers like Elsevier and the Nature Publishing Group but also by research organizations such as the European Molecular Biology Organization (EMBO) and the European Organization for Nuclear Research (CERN). The ORCID iD was developed as an overarching identifier based on software adapted from Thomson Reuters' ResearcherID system[9] and is now open source. By allowing to unambiguously identify authors of research publications, it responds to the problem that names of researchers are not unique, can be spelled differently and can change over time making it difficult to relate research publications to their authors (Wikipedia 2021c). To date approximately 11 million IDs have been assigned to authors (Wikipedia 2021c).

To get an ORCID iD researchers need to register themselves. On registering, researchers are provided with a profile to which they can

[9] Like the Web of Science ResearcherID, Elsevier has also set up a proprietary Scopus ID.

add their publications. ORCID has furthermore started to encourage researchers to integrate into their profile additional information about their CV, their funding, and their entire research output. Registered researchers can also agree to make their information available to organizations such as publishers, funders, or research organizations that have obtained ORCID membership. Through a member API ORCID members can have access to the profiles of individual researchers and their data. With the users' permission they can also include additional information to researchers' profiles. The ORCID iD is thus attempting to become an inclusive record of research careers encompassing a variety of information about individual academic careers and achievements. It is furthermore already "routinely used by academic-facing platforms as an authentication tool (such as the data repository Zenodo and some journal peer review systems), by publishers and journals to track article progress with authors, by institutions to build researcher performance profiles and also by research funders" (Klump et al. 2017: 3) that have started to include this information in their application process. In addition, research organizations have started "to update ORCID records and to register their employees and students for ORCID identifiers" (Klump et al. 2017: 8) making this information usable for internal monitoring and external reporting.

Persistent identifiers are developed not only for researchers but also for research organizations. The first identifier was the Ringgold ID which was established in 2003 at the request of the publishing industry to make institutional subscribers to publishers unambiguously identifiable because, like authors, organization names too can be spelled differently and change over time (Ringgold Inc. 2021). While Ringgold is designed to serve the needs of publishers helping them to connect different sets of information about the same customer (Ringgold Inc. 2021), the Global Research Identifier Database (GRID) was implemented by Digital Science in 2015. The GRID ID identifies organizations through information extracted from research funding grants and research paper affiliations and adds metadata such as "established dates, name aliases, acronyms and geolocation" as well as "links to external webpages such as Wikipedia and official websites" (GRID 2021a) and further persistent identifiers to them. It is exclusively linked to the database Dimensions from which it obtains data for creating GRID IDs. Simultaneously, the GRID ID can be used to draw data on organizational affiliations from the Dimensions database and to attribute it to a particular organization enabling the creation of an organization's record (GRID 2021b) which can be used for institutional reporting. The newcomer among the persistent identifiers for organizations is the Research Organization Registry (ROR), which was only established in 2019 based on an initiative by 17 organizations, among them Crossref, DataCite, and ORCID

(Ferguson et al. 2019: 14). To get started, the ROR relied on data from GRID, but was designed as an "an open, sustainable, usable, and unique identifier for every research organization in the world" (ROR n.d. a) aiming for the inclusion of comprehensive metadata. Its proclaimed goal is to provide a "proper description of relationships between contributors, contributions, research sponsors, publishers, and employers" (ROR n.d. b).

This short overview highlights that persistent identifiers simultaneously result from and contribute to the enormous growth of data and metadata about research and research practice. They serve to improve data quality by unambiguously identifying people, organizations, and objects, rendering data usable for different purposes. In addition, their registries provide APIs that allow for their interoperability with other systems and devices in various contexts. They are furthermore designed to be machine-readable[10] facilitating data processing and assessment through other devices. Persistent identifier registries also constantly produce new data through encouraging new entries within existing registries and the provision of additional metadata. Moreover, new persistent identifier registries are set up for further classes of objects such as data, software, grants, or conferences[11] contributing to the constant scalability of bibliometric infrastructure.

Persistent identifiers therefore play a decisive role in the linkage of data about research, researchers, and research organizations. Research practice can now be mapped from research funding to research results assigning output to individual researchers and research organizations.[12] They are announced as "an essential tool for resource management […] to ensure that the benefits of investment in research can be distributed and harvested over the long-term" (Dappert et al. 2017: 2). They are furthermore projected as contributing to the development of new "metrics around usage, reusage and other sorts of relationships between research objects" (Klump et al. 2017: 2). Persistent identifiers have become an indispensable means not only for attributing credit to researchers and research organizations for their scientific achievements, but also for making them much more accountable for the money they have spent.

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10 See Meadows et al. (2021).

11 See for an overview about ongoing initiatives Ferguson et al. (2019).

12 Check for initiatives such as the PID graph (Fenner and Aryani n.d.) or the Research graph (Research Graph Foundation n.d.).

Evaluative software and current research information systems

Bibliographic, citation, and altmetric data provided by citation indices and altmetric data aggregators are processed, linked, and analysed by a variety of software tools and current research information systems (CRIS) (see Figure 3). Software development sets in as early as the 1980s, since when it has accelerated and diversified. Already in 1997, Sylvan Katz and Diana Hicks observed the emergence of so called "desktop bibliometrics"[13] where "[a]dvanced scientometric tools are moving from the realm of the privileged few with access to mainframe and minicomputers to the desktop of researchers equipped with personal computers" (Katz and Hicks 1997: 141).

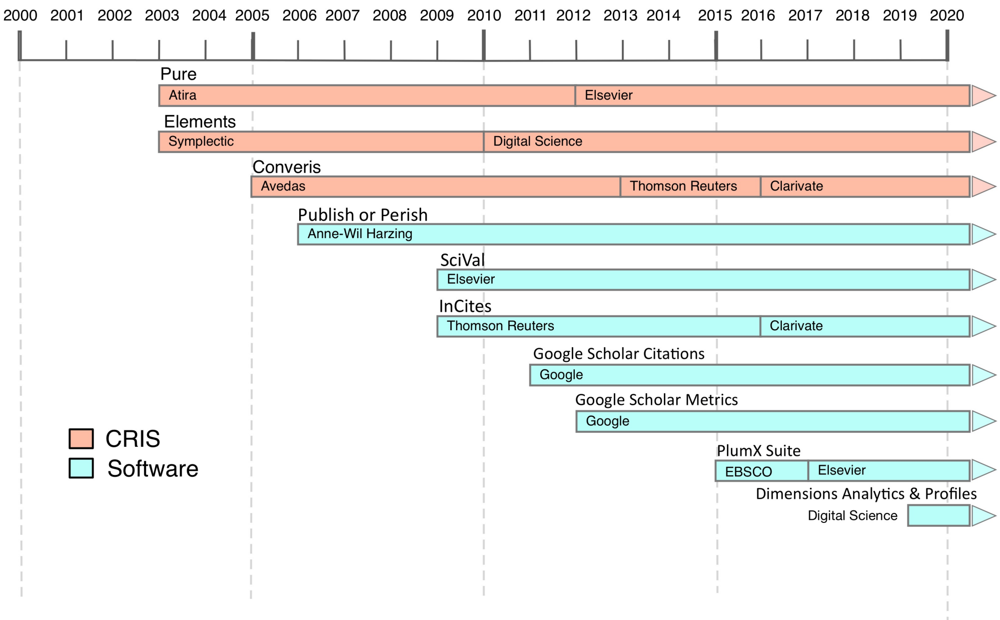

Figure 3. Development of software and current research information systems.
Source: Authors' own illustration.

The first major software product explicitly developed for evaluative purposes dates back to 2006, when management professor Anne-Wil Harzing developed the free software package Publish or Perish. It made citation analyses and a set of impact and output metrics based on bibliographic data from Google Scholar available to a wide audience ranging from individual researchers to librarians and research

[13] The term has recently been used in a different manner, denoting the application of bibliometrics by research managers and policy analysts, often including uninformed or even misuse of indicators (Bornmann 2020).

administrators (Harzing.com 2016a). The software had been initially designed to include research from disciplines that were not covered adequately in Web of Science and, in the meantime, has been extended to include Microsoft Academic, Scopus, and also Web of Science as databases for calculating individual-level impact metrics (Harzing.com 2016b). Invented one year after the introduction of the h-index, *Publish or Perish* has been and still is prominently used as an h-index calculator to support decisions for promotion, tenure, or funding applications (Harzing.com 2021).

Three years later, evaluative tools were rolled out on a larger scale through introduction of the commercial web-based software suites *SciVal* by Elsevier (Relx 2009) and *InCites* by Thomson Reuters (ISI Web of Knowledge 2009) in 2009. They permit a wide range of analytic functionalities packaged into several modules depending on the chosen subscription model of their users. They offer individual and organizational performance profiles, global comparisons with other research organizations, or expert searches (The Scholarly Kitchen 2014). They are designed to evaluate research productivity, research collaborations and impact as well as to offer benchmarking and reporting functionalities (Clarivate Analytics 2019a). In 2019, Digital Science also introduced a tool for research evaluation with *Dimensions Analytics* and *Dimensions Profiles*. The web applications build on Dimensions' data and can be used for complex analyses or for finding experts for reviews and collaborations and showcasing institutional research. *Dimensions Analytics* supports data exports to bibliometric mapping software and has integrated features from Altmetric.com (Dimensions 2021b, 2021c).

Drawing on data from the respective citation index of their providers these software tools enable the computation of research output and impact analyses as well as benchmarking functions (Clarivate Analytics n.d.; Elsevier 2021b). Research managers and administrators, academic librarians, and researchers themselves are the main targeted user groups for these products (Leydesdorff et al. 2016; Petersohn 2016). Their dashboards provide "enhanced visual data analysis" (Dimensions 2021b) with tables and multiple visual components based on graphs, maps, profiles, and plots, making them easily applicable.

Yet, the market for evaluative bibliometrics software is not dominated by proprietary products with restricted access alone. In 2011 and 2012, Google launched its free citation service *Google Citations* connected to *Google Scholar* profiles and the journal ranking *Google Metrics,* both delivering h-type and more citation metrics for authors and journals (Goldenfein et al. 2019). Compared to the three other software tools its functionalities are, however, limited. A major development in the market for analytical software tools has been triggered by artificial intelligence technologies such as machine learning and natural language processing that have not only become central technologies in the underlying databases but also in software programs. *SciVal* and *InCites* both proclaim to be "next generation analytics platforms" by incorporating these technologies (Elsevier 2021c; InCites 2021).

Current research information systems represent a distinct category within the bibliometric infrastructure because they consist of an integrated database and information system with a user interface for different applications. They integrate several different external and internal data sources such as bibliographic databases as well as internal human resources and financial systems for providing reports and producing outputs such as CV exports or content for organizational websites showcasing research (Sivertsen 2019). The most prominent current research information systems are Pure developed by the Danish company Atira (Relx 2012), Elements as a product of the British start-up Symplectic (Research Information 2015), both dating from 2003, and Converis, which was developed in 2005 by the German company Avedas (Information Today 2013).

These systems assume an increasingly important role not only in research reporting, assessment, and information management at the organizational level but also in supporting national research evaluation exercises as well as tenure programmes (Fondermann and van der Togt 2017; Kaltenbrunner and de Rijcke 2017; Lim 2021). Their potential has been recognized by Elsevier, Digital Science, and Thomson Reuters/Clarivate which acquired the three current research information systems, respectively in the years 2010 (Digital Science and Elements), 2012 (Elsevier and Pure), and 2013 (Thomson Reuters and Converis). As opposed to the administratively often less visible usage of evaluative software tools like *SciVal* and *InCites* in research organizations, current research information systems increasingly come with openly communicated, incentivized compliance policies in universities to foster digital collection and registration of research information. They furthermore increasingly represent a passage point for academics in research organizations that are required to register metadata about their research activities to be eligible for tenure programmes, promotion, or related assessment frameworks (Fondermann and van der Togt 2017; Kaltenbrunner and de Rijcke 2017; Piromalli 2019), or for having their research presented on the research organization's website.

Evaluative software tools and current research information systems thus play a key role in producing and assessing bibliometric data and providing meaning to it. They are tightly linked to and highly interoperable with other components of the bibliometric infrastructure. They provide APIs for connecting with other tools and draw on persistent identifiers to flexibly incorporate and link new (meta)data. Being structured in modules to perform distinct functions such as benchmarking or collaboration analysis, they are easily scalable. Whereas analytics software is confined to analysing data at the organizational level, current research information systems can even be scaled up from organizational to national level by means of integrating multiple data sources, enabled by APIs and persistent identifiers.

How evaluation is exactly done, however, is not a matter of only data content or indicators. While traditional indicators still form an integral part of these tools, claims for "predictive research analytics" have been raised. Providers of evaluative software contend that their advanced technologies not only allow for retrospective performance measurement. They also enable predictive analyses of future developments ranging from discovering trending topics to detecting potential high impact research. *Dimensions Analytics* is advertised as providing "enhanced discovery tools […] to deliver a full picture of past, current, and future research" (Dimensions 2021b). *SciVal* even claims to "enable […] users to envision alternate research groups by 'dragging and dropping' any researcher across the globe into hypothetical teams and gauge expected changes in performance by benchmarking 'fantasy' groups against existing groups" (EurekAlert 2011). Data scientists discuss "intelligent bibliometrics" as a promising (and profitable) new field arguing that "[t]raditional bibliometrics profile key topics and players using citation/co-citation and co-word statistics, but fail to identify complicated relationships to explain 'why' and 'how'" (Zhang et al. 2020: 1259). They claim that "[n]ovel bibliometric approaches, with the aid of advanced information technologies (e.g., machine learning and streaming data analytics), create new opportunities to uncover such relationships" (Zhang et al. 2020: 1259) enabling new kinds of complex analyses of research trends and future performance. Currently, publishers especially explore the potential of predictive analyses based on data from both citation databases and software tools for improving the performance and impact of their journals (Clarivate Analytics 2019b; Aspesi and Brand 2020). Yet, these predictive analyses might slowly be extended to the realm of national and organizational research assessment (Aspesi et al. 2019). The generative potential of software tools and current research information systems to constantly produce and link data on research and research practice has thus become a playground for testing new ways to channel research collaboration and to predict academic performance.

From indicator-based research evaluation to data-driven research analytics

Charting the development of bibliometric infrastructure within the last two decades, we have shown that citation databases, altmetric data aggregators, persistent identifiers, evaluative software tools, and current research information systems have experienced enormous growth in their content and functionalities. Citation databases are indexing an increasing variety of publication types, extending their coverage of subject fields and broadening their scope towards additional research products and outcomes such as books, patents, and more. Altmetric data aggregators are producing data on the reception of research outcomes in academia and society at large that are supposed to trace the "impact" of research beyond citations. Machine-readable persistent identifiers are created to unambiguously identify researchers, research organizations, and research objects linking them to additional metadata. And evaluative software tools and current research information systems are constantly enlarging their range of functionality to make use of these data and extract meaning from them.

Yet, it is not simply the sheer growth of these technologies for producing and assessing data about scientific practice and outcomes that has contributed to an ongoing proliferation of performance measurement in academia. It is in addition the increasing interoperability, scalability, and flexibility of these technologies and the datasets they produce that has moreover augmented the possibilities for academic evaluation. These material specificities of bibliometric infrastructure have generated a significant shift in the possibilities for practising evaluation of researchers and research organizations, giving way to data-driven research analytics based on what is digitally accessible and assessable.

The *interoperability* of different datasets and software tools through APIs and persistent identifiers allows for the linkage of various and constantly growing datasets through which data on researchers, research conditions, and research outcomes become related to one another. These linkages provide information not only about publication practices and their reception. They also strengthen belief in "return on investment". Relating particular grants and other sources of funding to researchers and research organizations allows for questions about the adequate allocation of resources rendering not only researchers but also funders accountable for how they spend their money.

Interoperability is also made available between databases and different software tools which provide the functionalities to draw meaning from these data. This interoperability of databases and software allows for the *scalability* of bibliometric infrastructure making it possible to constantly attach new data and functionalities to existing infrastructure. The scope of academic performance measurement can thus be permanently extended not only from the micro-level of individual researchers to comparisons between entire research organizations worldwide, but also in terms of new ideas for evaluation criteria and the evaluated subjects. The availability of new data such as mentions in policy documents (Overton n.d.) generates the potential to make these data usable for "policy impact" as a new evaluative criterion (Tattersall and Carroll 2018).

The scalability of the software and its functionalities also depend on the *flexibility* of data production and usage. Evaluative software tools and current research information systems exhibit generative potential by constantly extending their functionalities to integrate and assess new kinds of data and to extract meaning from them, making practices of research assessment increasingly data-driven. Moreover, the interoperability of databases and software through APIs and the machine-readability of data facilitated through persistent identifiers, their scalability, and their constant enlargement through the flexible integration and construction of new data generate an urge for prediction and trend analyses rather than retrospective evaluation of past achievements operationalized along predefined indicators. Evaluation of the past is turned into predictive analytics of the future.

These features of interoperability, scalability, and flexibility hold the generative potential to change academic performance measurement from indicator-based evaluation towards data-driven research analytics. They provide the material means for generating new evaluation categories as well as belief in the possibility of calculating and predicting successful research. Research analytics therefore not only claim to evaluate past research but generate an understanding of research practice as a predictable enterprise.

Conclusion

With our study on the development of bibliometric infrastructure, we discussed how the interoperability, scalability, and flexibility of bibliometric infrastructure contribute to an extension of indicator-based research evaluation towards data-driven research analytics highlighting how the material specificities of digital infrastructure generate new possibilities for the production and assessment of data in valuation processes. We argued that technology does not only have a performative effect on *how* evaluation is practised through predefined indicators and their inscription into technology but can furthermore generate a new understanding of what is actually evaluated. This is fostered by digital possibilities of producing and linking unprecedented masses of digitized data and the advancement of automated assessment technologies. The advent of data-driven research analytics catalysed through material specificities of digital infrastructure therefore holds a different approach from extracting meaning from data than does indicator-based research evaluation. It claims not only to extrapolate the future from past performance but moreover to genuinely discover novel topics, trends, and future achievements.

This is not only empirically relevant for understanding recent developments in the (e)valuation of academic performance. The data-drivenness of digital infrastructure also opens up new avenues for theory development in research on quantification. Quantification is so far understood as the production and communication of numbers that turn qualitative characteristics into quantities based on predefined metrics and indicators (Espeland and Stevens 2008; Mennicken and Espeland 2019). Quantification in this regard follows from operationalizing qualitative differences in terms of quantitative output according to a common metric. Yet, the data-drivenness of bibliometric infrastructure appears to work the other way round. Instead of constructing a priori a quantitative indicator for qualitative characteristics and performances, it is the massive production of digitized data and new assessment technologies from which follows how measurement and evaluation can be done (Krüger 2020). Thus, data-driven analytics do not systematically collect data based on operationalized indicators. Instead, it is the availability of large amounts of interlinked digital data subjected to algorithmic analysis that have the generative power to create new understanding of academic performance and scientific practice as such.

Yet, how these data are used is neither set nor predetermined through technology alone. It not only depends on their users (McCoy and Rosenbaum 2019; Lim 2021), but also on their providers. While we have referred to non-commercial datasets and tools such as ORCID or *Publish or Perish*, a substantial part of bibliometric infrastructure in use is owned by big private companies such as Clarivate, Elsevier, and Digital Science. Each of their product portfolios includes a current research information system and evaluative software tools that draw on their own respective citation databases. Bibliometric infrastructure has thus become a commercial product through creating – as Mirowski (2018) has put it – an encompassing "Panopticon of Science" that allows for "near real-time surveillance of the research process" (Mirowski 2018: 195).

Which part of the research process is subject to research analytics and under which premises is however still contingent. It depends on the potential "use cases" that their commercial providers advertise to win different kinds of customers even beyond researchers and research administration such as funders or publishers. Providers of research analytics follow the "institutional data imperative" (Fourcade and Healy 2017: 9) of modern organizations. They collect as much data as possible without any specific use in mind (see also Sadowski 2019). Consequently, building on the idea of "assetization" (Birch and Muniesa 2020) data on scientific practice have become an asset because they can constantly be repurposed for various uses depending on "data activation regimes" (Beauvisage and Mellet 2020: 77) or the "techcraft" (Birch et al. 2021: 2) that provide data with meaning and thus with economic value.

For our case of bibliometric infrastructure this implies that the assetization of data on scientific practices becomes possible through the material specificities of bibliometric infrastructure. Its interoperability and scalability allow for an increase in the amount of data – no matter if the data are provided by commercially operating enterprises such as Elsevier, Clarivate, or Digital Science or freely produced by non-profit organizations and later included in commercial products. The flexibility of these data allows for them to be put to use in various ways and contexts depending on how the functionalities of the evaluative software draw meaning from them. It thus appears to be the economic valuation of data on scientific practices – either as revenues for commercial providers or as return on investment for research management, policy agents, and funding agencies – that drives the extension from indicator-based research evaluation towards data-driven research analytics.

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References

Alaimo, Cristina, and Jannis Kallinikos. 2021. "Managing by Data: Algorithmic Categories and Organizing." *Organization Studies* 42(9): 1385–1407.

Aspesi, Claudio, and Amy Brand. 2020 "In Pursuit of Open Science, Open Access is not Enough." *Science* 368(6491): 574–577.

Altmetric. n.d. a. "The Donut and Altmetric Attention Score." https://www.altmetric.com/about-our-data/the-donut-and-score/, accessed December 22, 2021.

Altmetric. n.d. b. "Altmetric Details Page API Reference & Getting Started." http://api.altmetric.com/, accessed December 22, 2021.

Amoore, Louise, and Volha Piotukh. 2015. "Life beyond Big Data: Governing with Little Analytics." *Economy and Society* 44(3): 341–366.

Aspesi, Claudio, Nicole S. Allen, Raym Crow, Shawn Daugherty, Heather Joseph, Joseph T. W. McArthur, and Nick Shockey. 2019. "SPARC Landscape Analysis", March 29.

Aström, Fredrik. 2016. "Infrastructures as Analytical Framework for Mapping Research Evaluation Landscapes and Practices," Paper presented at Materiality and Social Dynamics of Information Infrastructures and Learning, Hindås, Sweden, October.

Baas, Jeroen, Michiel Schotten, Andrew Plume, Grégoire Côté, and Reza Karimi. 2020. "Scopus as a Curated, High-Quality Bibliometric Data

Source for Academic Research in Quantitative Science Studies." *Quantitative Science Studies* 1(1): 377–386.

Beauvisage, Thomas, and Kevin Mellet. 2020. "Datassets: Assetizing and Martketizing Personal Data." In *Assetization: Turning Things into Assets in Technoscientific Capitalism. Inside Technology*, edited by Kean Birch and Fabian Muniesa, 75–95. Inside technology. Cambridge, MA: The MIT Press.

Birch, Kean, D. T. Cochrane, and Callum Ward. 2021. "Data as Asset? The Measurement, Governance, and Valuation of Digital Personal Data by Big Tech." *Big Data & Society* 8(1).

Birch, Kean, and Fabian Muniesa (Eds.) 2020. *Assetization: Turning Things into Assets in Technoscientific Capitalism. Inside Technology.* Cambridge, MA: The MIT Press.

Birkle, Caroline, David A. Pendlebury, Joshua Schnell, and Jonathan Adams. 2020. "Web of Science as a Data Source for Research on Scientific and Scholarly Activity." *Quantitative Science Studies* 1(1): 363–376.

Björneborn, Lennart, and Peter Ingwersen. 2001. "Perspective of Webometrics." *Scientometrics* 50(1): 65–82.

Bornmann, Lutz. 2020. "Bibliometrics-Based Decision Trees (BBDTs) Based on Bibliometrics-Based Heuristics (BBHs): Visualized Guidelines for the Use of Bibliometrics in Research Evaluation." *Quantitative Science Studies* 1(1): 171–182.

Bowker, Geoffrey C., and Susan Leigh Star. 1999. S*orting Things Out: Classification and Its Consequences*. Cambridge, MA: The MIT Press.

Bowker, Geoffrey C., Julia Elyachar, Andrea Mennicken, Peter Miller, and Joanne Randa Nucho. 2019. "Introduction to Thinking Infrastructures." In *Thinking Infrastructures*, edited by Martin Kornberger, Geoffrey C. Bowker, Julia Elyachar, Andrea Mennicken, Peter Miller, Joanne Randa Nucho, and Neil Pollock. Special issue, *Research in the Sociology of Organizations* (62): 1–13.

boyd, danah, and Kate Crawford. 2012. "Critical Questions for Big Data." *Information, Communication & Society* 15(5): 662–679.

Büchner, Stefanie. 2018. "Digitale Infrastrukturen – Spezifik, Relationalität und die Paradoxien von Wandel und Kontrolle." *Arbeits- und Industriesoziologische Studien* 11(2): 279–293.

Butler, Linda. 2003. "Explaining Australia's Increased Share of ISI Publications – The Effects of a Funding Formula Based on Publication Counts." *Research Policy* 32(1): 143–155.

Clarivate Analytics. n.d. "InCites Help. About the Indicators Handbook." http://help.prod-incites.com/inCites2Live/indicatorsGroup/aboutHandbook.html, accessed December 22, 2021.

Clarivate Analytics. 2019a. "Datasheet Incites." https://clarivate.com/webofsciencegroup/wp-content/uploads/sites/2/2019/09/My_Org-Fact_Sheet-Web-of-Science-Group-2019.pdf, accessed December 22, 2021.

Clarivate Analytics. 2019b. "The Web of Science Group Launches New Publisher Analytics Reports." https://clarivate.com/webofsciencegroup/news/the-web-of-science-group-launches-new-publisher-analytics-reports/, accessed May 15, 2022.

Cronin, Blaise. 2005. *The Hand of Science: Academic Writing and Its Rewards*. Lanham, MD: Scarecrow Press.

Crossref. 2020a. "Event Data." https://www.crossref.org/services/event-data/, accessed December 22, 2021.

Crossref. 2020b. "History." https://www.crossref.org/about/history/, accessed December 22, 2021.

Crossref. 2020c. "Funder Registry." https://www.crossref.org/services/funder-registry/, accessed December 22, 2021.

Dappert, Angela, Adam Farquhar, Rachael Kotarski, and Kirstie Hewlett. 2017. "Connecting the Persistent Identifier Ecosystem: Building the Technical and Human Infrastructure for Open Research." *Data Science Journal 16*.

de Rijcke, Sarah, and Alexander Rushforth. 2015. "To Intervene or Not to Intervene; Is That the Question? On the Role of Scientometrics in Research Evaluation." *Journal of the Association for Information Science and Technology* 66(9): 1954–1958.

de Rijcke, Sarah, Paul F. Wouters, Alex D. Rushforth, Thomas P. Franssen, and Björn Hammarfelt. 2016. "Evaluation Practices and Effects of Indicator Use – a Literature Review." *Research Evaluation* 25(2): 161–169.

Debackere, Koenraad, Wolfgang Glänzel, and Bart Thijs. 2019. "Scientometrics Shaping Science Policy and Vice Versa, the ECOOM Case." In *Springer Handbook of Science and Technology Indicators*, edited by Wolfgang Gänzel, Henk F. Moed, Ulrich Schmoch, and Mike Thelwall, 447–464. Cham: Springer International.

Delfanti, Alessandro. 2021. "The Financial Market of Ideas: A Theory of Academic Social Media." *Social Studies of Science* 51(2): 259–276.

Dellavalle, Robert, Eric Hester, Lauren Heilig, Amanda Drake, Jeff Kuntzman, Marla Graber, and Lisa Schilling. 2003. "Going, Going, Gone: Lost Internet References." *Science* 302(5646): 787–788.

Derrick, G.E., and V. Pavone. 2013. "Democratising Research Evaluation: Achieving Greater Public Engagement with Bibliometrics-Informed Peer Review." *Science and Public Policy* 40(5): 563–575.

Dimensions. 2021a. "Linked Research Data from Idea to Impact." https://www.dimensions.ai/, accessed December 22, 2021.

Dimensions. 2021b. "Dimensions Analytics." https://www.dimensions.ai/products/dimensions-analytics/, accessed December 22, 2021.

Dimensions. 2021c. "Dimensions Profiles." https://www.dimensions.ai/products/dimensions-profiles/, accessed December 22, 2021.

Elsevier. 2021a. "SciVal." https://www.elsevier.com/solutions/scival, accessed December 22, 2021.

Elsevier. 2021b. "Research Metrics Guidebook." https://www.elsevier.com/research-intelligence/resource-library/research-metrics-guidebook, accessed December 22, 2021.

Elsevier. 2021c."See What SciVal Can Do For You." https://www.elsevier.com/solutions/scival/features, accessed December 22, 2021.

Espeland, Wendy Nelson, and Mitchell L. Stevens. 2008. "A Sociology of Quantification." *Archives Europeennes de Sociologie* 49(3): 401–436.

EurekAlert. 2011. "Elsevier Launches SciVal Strata to Enhance Research Evaluation." https://www.eurekalert.org/news-releases/888677, accessed December 22, 2021.

Fenner, Martin, and Amir Aryani. n.d. "Introducing the PID Graph." https://www.project-freya.eu/en/blogs/blogs/the-pid-graph, accessed December 22, 2021.

Ferguson, Christine, Jo McEntrye, Vasily Bunakov, Simon Lambert, Stephanie van der Sandt, Rachael Kotarski, Sarah Stewart, Andrew MacEwan, Martin Fenner, Patricia Cruse, René van Horik, Tina Dohna, Ketil Koop-Jacobsen, Uwe Schindler, and Siobhan McCafferty. 2019. "D3.1 Survey of Current PID Services Landscape." *FREYA Report* (rev. version).

Fondermann, Philipp, and Peter L. van der Togt. 2017. "How Wageningen University and Research Centre Managed to Influence Researchers' Publishing Behaviour Towards More Quality, Impact and Visibility." *Procedia Computer Science* 106: 204–211.

Fourcade, Marion, and Kieran Healy. 2017. "Seeing Like a Market." *Socio-Economic Review* 15(1): 9–29.

Franzen, Martina. 2015. "Der Impact Faktor war gestern: Altmetrics und die Zukunft der Wissenschaft." *Soziale Welt* 66(2): 225–242.

Furner, Jonathan. 2014. "The Ethics of Evaluative Bibliometrics." In *Beyond Bibliometrics: Harnessing Multidimensional Indicators of Scholarly Impact,* edited by Blaise Cronin and Cassidy R. Sugimoto, 85–107. Cambridge, MA: The MIT Press.

Garfield, Eugene. 1964. "'Science Citation Index' – a New Dimension in Indexing." *Science* 144(3619): 649–654.

Gingras, Yves. 2016. *Bibliometrics and Research Evaluation. History and Foundations of Information Science.* Cambridge, MA: The MIT Press.

Godin, Benoît. 2006. "On the Origins of Bibliometrics." *Scientometrics* 68(1): 109–133.

Goldenfein, Jake, Sebastian Benthall, Daniel Griffin, and Eran Toch. 2019. "Private Companies and Scholarly Infrastructure – Google Scholar and Academic Autonomy." *Critical Reflections,* Cornell Tech.

GRID (Global Research Identifier Database). 2021a. "Policies." https://grid.ac/pages/policies, accessed December 22, 2021.

GRID (Global Research Identifier Database). 2021b. "Disambiguator." https://grid.ac/disambiguate, accessed December 22, 2021.

Hammarfelt, Björn, Gustaf Nelhans, Pieta Eklund, and Fredrik Åström. 2016. "The Heterogeneous Landscape of Bibliometric Indicators: Evaluating

Models for Allocating Resources at Swedish Universities.” *Research Evaluation* 25(3): 292–305.

Harzing.com. 2016a. “Publish or Perish.” http://www.harzing.com/pop.htm, accessed December 22, 2021.

Harzing.com. 2016b. “Data Sources.” https://harzing.com/resources/publish-or-perish/manual/using/data-sources, accessed December 22, 2021.

Harzing.com. 2021. “The Changing Usage of Publish or Perish Over the Years: Where, Why, When, What & Who?” https://harzing.com/blog/2021/01/the-changing-usage-of-publish-or-perish-over-the-years-where-why-when-what-who, accessed December 22, 2021.

Haustein, Stefanie. 2016. “Grand Challenges in Altmetrics: Heterogeneity, Data Quality and Dependencies.” *Scientometrics* 108(1): 413–423.

Haustein, Stefanie, Cassidy Sugimoto, and Vincent Larivière. 2015. “Guest Editorial: Social Media in Scholarly Communication.” *Aslib Journal of Information Management* 67(3).

Haustein, Stefanie, Timothy D. Bowman, and Rodrigo Costas. 2016. “Interpreting ‘Altmetrics’: Viewing Acts on Social Media through the Lens of Citation and Social Theories.” In *Theories of Informetrics and Scholarly Communication: A Festschrift in Honor of Blaise Cronin*, edited by Cassidy R. Sugimoto, 372–406. Berlin: De Gruyter Mouton.

Hazelkorn, Ellen. 2011. *Rankings and the Reshaping of Higher Education: The Battle for World-Class Excellence*. Houndmills, Basingstoke: Palgrave Macmillan.

Herb, Ulrich. 2019. “Überwachungskapitalismus und Wissenschaftssteuerung.” https://www.heise.de/tp/features/Ueberwachungskapitalismus-und-Wissenschaftssteuerung-4480357.html?seite=all, accessed December 22, 2021.

Herzog, Christian, Daniel Hook, and Stacy Konkiel. 2020. “Dimensions: Bringing down Barriers between Scientometricians and Data.” *Quantitative Science Studies* 1(1): 387–395.

Hicks, Diana. 2012. “Performance-Based University Research Funding Systems.” *Research Policy* 41(2): 251–261.

Hug, Sven E., Michael Ochsner, and Martin P. Brändle. 2017. "Citation Analysis with Microsoft Academic." *Scientometrics* 111(1): 371–378.

InCites. 2021. “AI-powered Insights for Digital Business.” https://www.incites.com/, accessed December 22, 2021.

Information Today. 2013. “Thomson Reuters Enhances Research and Analytics Tools.” http://newsbreaks.infotoday.com/Digest/Thomson-Reuters-Enhances-Research-and-Analytics-Tools-93825.asp, accessed December 22, 2021.

International DOI Foundation. 2015. “The DOI Handbook.” https://www.doi.org/doi_handbook/1_Introduction.html, accessed December 22, 2021.

International DOI Foundation. 2021. “Factsheet. Key Facts on Digital Object Identifier System.” https://www.doi.org/factsheets/DOIKeyFacts.html, accessed December 22, 2021.

ISI Web of Knowledge. 2009. "Series of Webinars – Demonstration of InCites." https://wok.mimas.ac.uk/news/2009/20091007.html, accessed December 22, 2021.

Jappe, Arlette. 2020. "Professional Standards in Bibliometric Research Evaluation? A Meta-Evaluation of European Assessment Practice 2005–2019." *PloS one* 15(4): e0231735.

Kaltenbrunner, Wolfgang, and Sarah de Rijcke. 2017. "Quantifying 'Output' for Evaluation: Administrative Knowledge Politics and Changing Epistemic Cultures in Dutch Law Faculties." *Science and Public Policy* 44(2): 284–293.

Katz, J. Sylvan, and Diana Hicks. 1997. "Desktop Scientometrics." *Scientometrics* 38(1): 141–153.

Kiviat, Barbara. 2019. "The Moral Limits of Predictive Practices: The Case of Credit-Based Insurance Scores." *American Sociological Review* 84(6): 1134–1158.

Klump, Jens, Fiona Murphy, Tobias Weigel, and Mark Parsons. 2017. "Editorial: 20 Years of Persistent Identifiers – Applications and Future Directions." *Data Science Journal* 16.

Krüger, Anne K. 2020. "Quantification 2.0? Bibliometric Infrastructures in Academic Evaluation." *Politics and Governance* 8(2): 58–67.

Lagotto. n.d. a. "About Lagotto." https://www.lagotto.io/, accessed December 22, 2021.

Lagotto. n.d. b. "Public Library of Science (PLOS)." https://www.lagotto.io/plos/, accessed December 22, 2021.

Leydesdorff, Loet, Paul Wouters, and Lutz Bornmann. 2016. "Professional and Citizen Bibliometrics: Complementarities and Ambivalences in the Development and Use of Indicators—a State-of-the-Art Report". *Scientometrics* 109(3): 2129–2150.

Lim, Miguel Antonio. 2021. "Governing Higher Education: The PURE Data System and the Management of the Bibliometric Self." *Higher Education Policy* 34(1): 238–253.

Lin, Jennifer, and Martin Fenner. 2013. "Altmetrics in Evolution: Defining and Redefining the Ontology of Article-Level Metrics." I*nformation Standards Quarterly* 25(2): 20–26.

López-Cózar, Emilio Delgado, Enrique Orduna-Malea, and Alberto Martín-Martín. 2019. "Google Scholar as a Data Source for Research Assessment." In *Springer Handbook of Science and Technology Indicators*, edited by Wolfgang Gänzel, Henk F. Moed, Ulrich Schmoch, and Mike Thelwall, 95–127. Cham: Springer International.

Lupton, Deborah. 2016. *The Quantified Self: A Sociology of Self-Tracking*. Cambridge: Polity Press.

McCoy, Chase, and Howard Rosenbaum. 2019. "Uncovering Unintended and Shadow Practices of Users of Decision Support System Dashboards in Higher Education Institutions." *Journal of the Association for Information Science and Technology* 70(4): 370–384.

MacKenzie, Donald, and Judy Wajcman. 1999. "Introductory Essay: The Social Shaping of Technology." In *The Social Shaping of Technology,* edited by Donald A. MacKenzie and Judy Wajcman. Maidenhead: Open University Press. http://eprints.lse.ac.uk/28638/, accessed December 22, 2022.

Martín-Martín, Alberto, Mike Thelwall, Enrique Orduña-Malea, and Emilio Delgado López-Cózar. 2021. "Google Scholar, Microsoft Academic, Scopus, Dimensions, Web of Science, and OpenCitations' COCI: A Multidisciplinary Comparison of Coverage via Citations." *Scientometrics* 126(1): 871–906.

Mayer-Schönberger, Viktor, and Kenneth Cukier. 2013. *Big Data: A Revolution That Will Transform How We Live, Work and Think*. London: Murray.

Meadows, Alice, Laurel L. Haak, and Josh Brown. 2019. "Persistent Identifiers: The Building Blocks of the Research Information Infrastructure." *Insights* 32(1).

Meadows, Alice, Helena Cousijn, Maria Gould, Ginny Hendricks, Julie Petro, and Natasha Simons. 2021. "PIDs 101: A Beginners' Guide to Persistent Identifiers." Presentation.

Mennicken, Andrea, and Wendy Nelson Espeland. 2019. "What's New with Numbers? Sociological Approaches to the Study of Quantification." *Annual Review of Sociology* 45(1): 223–245.

Mennicken, Andrea, and Martin Kornberger. 2021. "From Performativity to Generativity: Valuation and Its Consequences in the Context of Digitization." *Kölner Zeitschrift für Soziologie und Sozialpsychologie* 73: 451–478.

Microsoft. 2021a. Next Steps for Microsoft Academic – Expanding into New Horizons." https://www.microsoft.com/en-us/research/project/academic/articles/microsoft-academic-to-expand-horizons-with-community-driven-approach/, accessed December 22, 2021.

Microsoft. 2021b. "Microsoft Academic." https://academic.microsoft.com/home, accessed December 22, 2021.

Mirowski, Philip. 2018. "The Future(s) of Open Science." *Social Studies of Science* 48(2): 171–203.

Moed, Henk F. 2007. "The Future of Research Evaluation Rests with an Intelligent Combination of Advanced Metrics and Transparent Peer Review". *Science and Public Policy* 34(8): 575–583.

Moed, Henk. F. 2017. *Applied Evaluative Informetrics. Qualitative and Quantitative Analysis of Scientific and Scholarly Communication*. Cham: Springer International.

Narin, Francis. 1976. *Evaluative Bibliometrics: The Use of Publication and Citation Analysis in the Evaluation of Scientific Activity.* Report to the National Science Foundation. Cherry Hill, NJ: Computer Horizons.

Nicholas, David, Eti Herman, Hamid R. Jamali, Abdullah Abrizah, Cherifa Boukacem-Zeghmouri, Jie Xu, Blanca Rodríguez-Bravo, Anthony Watkinson, Tatiana Polezhaeva, and Marzena Świgon. 2020. "Millennial

Researchers in a Metric-Driven Scholarly World: An International Study." *Research Evaluation* 29(3): 263–274.

Nuredini, Kaltrina, Steffen Lemke, and Isabella Peters. 2021. "4.3 Social Media and Altmetrics." In *Handbook Bibliometrics*, edited by Rafael Ball, 201–214. Berlin: De Gruyter Saur.

OpenAlex. 2022. "About the Data." https://docs.openalex.org/about-the-data-1, accessed May 15, 2022.

Orduña-Malea, Enrique, Alberto Martín-Martín, Juan M. Ayllon, and Emilio Delgado López-Cózar. 2014. "The Silent Fading of an Academic Search Engine: The Case of Microsoft Academic Search." *Online Information Review* 38(7): 936–953.

Orlikowski, Wanda J., and Susan V. Scott. 2008. "Sociomateriality: Challenging the Separation of Technology, Work and Organization." The Academy of Management Annals 2(1): 433–474.

Ortega, José-Luis. 2020. "Altmetrics Data Providers: A Meta-Analysis Review of the Coverage of Metrics and Publication." *El Profesional de la Información* 29(1): 1–23.

Overton. n.d.. "Is Your Work Influencing Policy?" https://www.overton.io/, accessed December 22, 2021.

Paskin, Norman. 2010. "Digital Object Identifier (DOI®) System." *In Encyclopedia of Library and Information Sciences,* 3rd edn, edited by Marcia J. Bates and Mary N. Maack, 1586–5392. Boca Raton, FL: CRC Press.

Petersohn, Sabrina. 2016. "Professional Competencies and Jurisdictional Claims in Evaluative Bibliometrics: The Educational Mandate of Academic Librarians", *Education for Information* 32(2): 165–193.

Petersohn, Sabrina, and Thomas Heinze. 2018. "Professionalization of Bibliometric Research Assessment. Insights from the History of the Leiden Centre for Science and Technology Studies (CWTS)." *Science and Public Policy* 45(4): 565–578.

Piromalli, Leonardo. 2019. "Research Information Management in Italy. The IRIS Platformised Infrastructure as a Sociotechnical Device." S*cuola democratica* 4: 297–319.

Pollock, Neil, and Robin Williams. 2007. "Technology Choice and Its Performance: Towards a Sociology of Software Package Procurement." *Information and Organization* 17(3): 131–161.

Porter, Theodore. 1995. *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life*. Princeton, NJ: Princeton University Press.

Preda, Alex. 2006. "Socio-Technical Agency in Financial Markets." *Social Studies of Science* 36(5): 753–782.

Priem, Jason. 2014. "Altmetrics." *In Beyond Bibliometrics: Harnessing Multidimensional Indicators of Scholarly Impact,* edited by Blaise Cronin and Cassidy R. Sugimoto, 263–287. Cambridge, MA: The MIT Press.

Priem, Jason, and Heather Piwowar. 2012. "The Launch of ImpactStory: Using Altmetrics to Tell Data-Driven Stories." https://blogs.lse.ac.uk/

impactofsocialsciences/2012/09/25/the-launch-of-impactstor/, accessed December 22, 2021.

Priem, Jason, Dario Taraborelli, Paul Groth, and Cameron Neylon. 2010. "Altmetrics: A Manifesto." http://altmetrics.org/manifesto, accessed December 22, 2021.

Pritchard, Alan. 1969. "A Statistical Bibliography or Bibliometrics." *Journal of Documentation* 25(4): 348–349.

Relx. 2009. "Elsevier Launches SciVal Spotlight." https://www.relx.com/media/press-releases/archive/29-06-2009, accessed December 22, 2021.

Relx. 2012. "Elsevir Acquires Atira, a Provider of Research Management Solutions. https://www.relx.com/media/press-releases/archive/15-08-2012, accessed December 22, 2021.

Research Graph Foundation. n.d. "Research Graph Schema." https://researchgraph.org/, accessed December 22, 2021.

Research Information. 2015. "'A Taste for Openness and Change'." https://www.researchinformation.info/issue/octobernovember-2015, accessed December 22, 2021.

Ringgold Inc. 2021. "Ringgold Identifier." https://www.ringgold.com/ringgold-identifier/, accessed December 22, 2021.

ROR. n.d. a. "About." https://ror.org/scope/, accessed December 22, 2021.

ROR. n.d. b. "Scope." https://ror.org/scope/, accessed December 22, 2021.

Sadowski, Jathan. 2019. "When Data Is Capital: Datafication, Accumulation, and Extraction." *Big Data & Society* 6(1).

The Scholarly Kitchen. 2014. "Interview with Thomson Reuters: InCites Platform Offers New Analytics and Transparency." https://scholarlykitchen.sspnet.org/2014/08/08/qa-with-thomson-reuters-incites-platform-offers-new-analytics-and-transparency/, accessed December 22, 2021.

Scopus. 2019. "PlumX Metrics API Now Available for Scopus Subscribers." online: https://blog.scopus.com/topics/plumx-metrics#:~:text=PlumX%20Metrics%20is%20Plum%20Analytics%E2%80%99%20comprehensive%2C%20item-level%20metrics,chapters%2C%20and%20many%20more%29%20in%20the%20online%20environment, accessed December 22, 2021.

Sivertsen, Gunnar. 2019. "Developing Current Research Information Systems (CRIS) As Data Sources for Studies of Research." In *Springer Handbook of Science and Technology Indicators*, edited by Wolfgang Glänzel, Henk F. Moed, Ulrich Schmoch, and Mike Thelwall, 667–683. Cham: Springer International.

Star, Susan Leigh, and Karen Ruhleder. 1996. "Steps Toward an Ecology of Infrastructure. Design and Access for Large Information Spaces." *Information Systems Research* 7(1): 111–134.

Star, Susan Leigh, and Anselm Strauss. 1999. "Layers of Silence, Arenas of Voice. The Ecology of Visible and Invisible Work." *Computer Supported Cooperative Work* 8(1–2): 9–30.

Tattersall, Andy and Christopher Carroll. 2018. "What Can Altmetric.com Tell Us about Policy Citations of Research? An Analysis of Altmetric.com Data for Research Articles from the University of Sheffield." *Frontiers in Research Metrics and Analytics* 2

Teixeira da Silva, Jaime A., and Aamir Raoof Memon. 2017. "CiteScore: A Cite for Sore Eyes, or a Valuable, Transparent Metric?" *Scientometrics* 111(1): 553–556.

Thelwall, Mike, Liwen Vaughan, and Lennart Björneborn. 2006. "Webometrics." *Annual Review of Information Science and Technology* 39(1): 81–135.

Tilson, David, Kalle Lyytinen, and Carsten Sørensen. 2010. "Research Commentary —Digital Infrastructures: The Missing IS Research Agenda." *Information Systems Research* 21(4): 748–759.

Unternährer, Markus. 2021. "The Order of Recommendations." *Kölner Zeitschrift für Soziologie und Sozialpsychologie* 73: 397–423.

van Raan, Anthony. 2019. "Measuring Science: Basic Principles and Application of Advanced Bibliometrics." In *Springer Handbook of Science and Technology Indicators,* edited by Wolfgang Glänzel, Henk F. Moed, Ulrich Schmoch, and Mike Thelwall, 237–280. Cham: Springer International.

Wagner, Erica L., Jodie Moll, and Sue Newell. 2011. "Accounting Logics, Reconfiguration of ERP Systems and the Emergence of New Accounting Practices: A Sociomaterial Perspective." *Management Accounting Research* 22(3): 181–197.

Wang, Kuansan, Zhihong Shen, Chiyuan Huang, Chieh-Han Wu, Yuxiao Dong, and Anshul Kanakia. 2020. "Microsoft Academic Graph: When Experts Are Not Enough." *Quantitative Science Studies* 1(1): 396–413.

Wikipedia. 2021a. "Altmetric." https://en.wikipedia.org/wiki/Altmetric, accessed December 22, 2021.

Wikipedia. 2021b. "Plum Analytics." https://en.wikipedia.org/wiki/Plum_Analytics, accessed December 22, 2021.

Wikipedia. 2021c. "ORCID." https://en.wikipedia.org/wiki/ORCID#cite_ref-8, accessed December 22, 2021.

Wouters, Paul. 1999. "The Citation Culture." PhD diss. Universiteit van Amsterdam. http://garfield.library.upenn.edu/wouters/wouters.pdf.

Zahedi, Zohreh, and Rodrigo Costas. 2018. "General Discussion of Data Quality Challenges in Social Media Metrics: Extensive Comparison of Four Major Altmetric Data Aggregators." *PloS one* 13(5).

Zhang, Yi, Alan L. Porter, Scott Cunningham, Denise Chiavetta, and Nils Newman. 2020. "Parallel or Intersecting Lines? Intelligent Bibliometrics for Investigating the Involvement of Data Science in Policy Analysis." *IEEE Transactions on Engineering Management.*

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