The Regional Impact of Single-Site and Distributed Research Infrastructures Using the Example of DORIS and CTAO

Stephan Haid

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1 Introduction

Large-scale research facilities can take a number of forms including distributed research infrastructures, a network of distributed instruments that are geographically scattered, and single-sited research infrastructures but also virtual research infrastructures.

This article addresses two very different research infrastructures. The first and major part of the article is an ex-post evaluation of the single-sited DORIS storage ring located at DESY in Hamburg. This case very impressively demonstrated how a major research infrastructure could be successfully adapted to meet the developing requirements in science, thus providing research opportunities and long-term sustainability to scientific communities over many decades. The described ex-post evaluation of this unique research infrastructure (see Sect. 2 "Ex-post Evaluation of the Socio-economic Impact of DORIS") is a condensed reproduction of the article "The socio-economic impact of DORIS" by Lehner and Haid [1].

The third section (see Sect. 3 "Ex-ante Consideration of the Socio-Economic Impact of CTAO") of the article discusses the societal impact of the Cherenkov Telescope Array Observatory (CTAO), the first ground-based gamma-ray observatory with two telescope arrays on two different remote sites located in the Northern hemisphere on La Palma and in the southern hemisphere in the Atacama Desert in Chile.

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J. Gutleber and P. Charitos (eds.), *The Economics of Big Science 2.0*, Science Policy Reports, https://doi.org/10.1007/978-3-031-60931-2_6

Moreover, the headquarters of the CTAO are located in Italy in Bologna, and the Science Data Management Centre (SDMC) in Zeuthen, Germany.

2 Ex-post Evaluation of the Socio-economic Impact of DORIS

The 'Doppel-Ring Speicheranlage' DORIS at DESY in Hamburg [2] was built as a multi-GeV storage ring more than 50 years ago as the first of its kind. During its entire lifetime between 1974 and 2013 it has generated a tremendous variety of scientific findings and applications in the fields of particle physics, accelerator science and technology, photon science and in the life sciences. Generations of researchers have used DORIS to generate new knowledge and to pioneer, develop and test innovative experimental methods, instrumentation and related technologies that have subsequently been applied at other research laboratories all over the world and in industry. Hundreds of doctoral students and postdoctoral researchers earned their first merits at DORIS. Countless scientific cooperation was forged between national, international, and often interdisciplinary, teams to carry out joint experiments in Hamburg and many of these connections still exist today and have since then been firmly strengthened on institutional grounds building the core of the multidisciplinary science and innovation campus around DESY in Hamburg-Bahrenfeld.

The nearly 40 years of operation of DORIS represent a unique opportunity for a lifetime analysis of a multidisciplinary facility impacting various scientific and technological fields, promoting the building new scientific communities and creating strong networks that still exist today. In the following, an attempt will be made to highlight some of DORIS relevant impacts and illustrate its effects on the development of the science campus in Hamburg-Bahrenfeld.

a. The storage DORIS at DESY

During the entire lifetime of DORIS between 1974 and 2013 it went through three distinct phases [3]. During its first phase as a new type of accelerator known as a storage ring with colliding electron and positron beams designed, the experiments at DORIS produced most important findings to establish Standard Model of particle physics which was still new at that time.

The use of synchrotron radiation (SR), which was originally seen as a byproduct of the accelerator's operation opened up a plethora of new scientific opportunities at DORIS with truly impressive applications in physics, materials/nano sciences, geoscience, chemistry and with profound impact in biology/life sciences.

In a second phase of DORIS (DORIS II) a new lab, the so-called Hamburg Synchrotron Radiation Laboratory HASYLAB was opened in 1981 with the goal to meet the increasing demand and to better organize SR-related research at DORIS. Soon, it became an internationally renowned facility and one of the incubators of modern and successful research with SR worldwide. In this period, particle physicists and HASYLAB researchers shared the same storage ring in the 1980s.

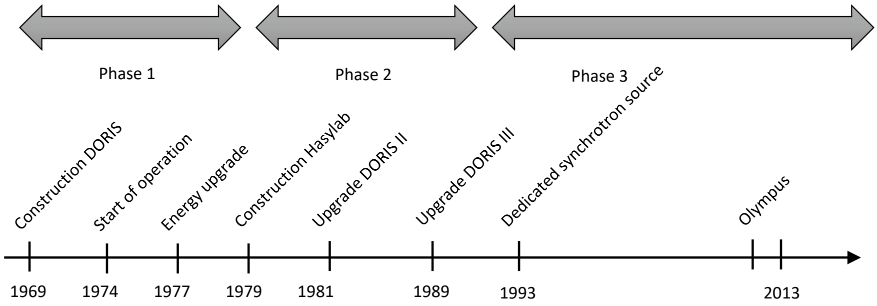

Fig. 1 The scientific life of DORIS in three distinct phases. *Credits* S. Haid

By the end of 1980s a further upgrade to the facility was proposed in order to accommodate the increasing demand for SR users and to stay competitive with other international facilities. In this third phase of DORIS one of the two straight sections was replaced with a curved section that would be fitted with integrated special magnets known as wigglers and undulators. This enabled the number of measuring stations to be increased and also improved the quality and intensity of the X-ray beams considerably. In 1993, almost 20 years after the first beams in DORIS, particle physics stopped and the ring became a dedicated SR facility (Fig. 1).

Research infrastructures such as DORIS were built and operated with a primary scientific mission and with the goal to contribute to the national and international stock of knowledge and to its dissemination and diffusion into other areas. It is well beyond the scope of this paper to record the scientific impact that materialized over the 40 years of the lifetime of DORIS. Instead, the other dimensions of socio-economic benefits of research infrastructures in context of people, economy and region will be addressed in the following.

b. Impact on people

Research facilities in basic science such as DORIS are not only promoting scientific knowledge and stimulating economic growth, but also strongly influencing the people working there and enhancing their capacities. During the service of DORIS (1974–2013), several thousands of people developed, maintained and scientifically exploited the facility. Next to administrative, technical and scientific staff of DESY, these included external users from a wide range of disciplines.

To visualise the career paths of doctoral degree recipients who worked at DORIS and to analyse the acquirement and transfer of skills into other sectors of employment, a survey among all known former DORIS graduate students was conducted by DESY. These included Ph.D. students employed by DESY, EMBL and several universities in Germany and abroad. The idea of the study (carried out in 2015) was to serve as an explicit proxy to track the transfer and utilisation of skills and knowledge created at DORIS in all fields of employment and all sectors of the economy.

In the following, some of the main findings of the survey are summarized:

- The training at large research infrastructures like DORIS enables students to follow careers also outside of public science and research. Even in their first job after the Ph.D., 22% started a career in the private sector. 10% of the students became entrepreneurs, of which 67% had employees.
- Regarding the Ph.D. students in the private sector, the data show major accumulations in the sectors information technology (IT) and healthcare, which will both gain increasing importance in the future due to the megatrends related to the technological and demographic change of society.
- To all appearances, the Ph.D. students did not only gain specific scientific skills and knowledge related to their research area, but also non-specific knowledge and soft skills that are even more valuable for the private sector. Among the five most important skills that the former students acquired during their Ph.D. work, only one refers to science (research methodologies/techniques). Instead, problem solving, team working, creative thinking and independent working were considered the most useful for their subsequent careers.
- Working at the research facility laid the foundations for successful professional careers of the students within or outside the commercial world. Only five years after graduation, more than half of the former DORIS Ph.D. students were responsible for their own budget (55%) and 45% led their own staff. In the long run (current position), 71% managed a budget and 69% had personal staff, clearly indicating an executive position.

Although fundamental science sometimes seems to be vague and hardly application-oriented, the skills that people gain are all the more applied—they solve concrete problems. Besides being trained in scientific methods and techniques, the Ph.D. students at DORIS (and the same most certainly applies to other large-scale research facilities) learn how to manage projects and find creative and innovative solutions in international and interdisciplinary teams (Fig. 2).

c. Impact on the economy

The economic effects of research facilities are manifold. Here we distinguish between direct and indirect economic added value and the effect of research infrastructures on economic innovation.

The construction and development of DORIS demanded major financial investments which generated economic impacts mainly to the metropolitan area of Hamburg and northern Germany, but also beyond. A reasonable method to elaborate these effects is a multi-stage, regionalized input–output-analysis [4], in which financial effects are decomposed into regional and sectoral effects. Essentially one would like to understand the economic "chain reaction" of investments considering that money is re-spent again and again in the economy, creating jobs and income for businesses and other workers.

There are three different aspects of the financial impact to be considered: at first the primary input triggers the so-called direct effects. They include on the one hand revenues of the direct suppliers (direct sales effects) and on the other hand the jobs that were directly generated at the facility (direct employment effects). Secondly,

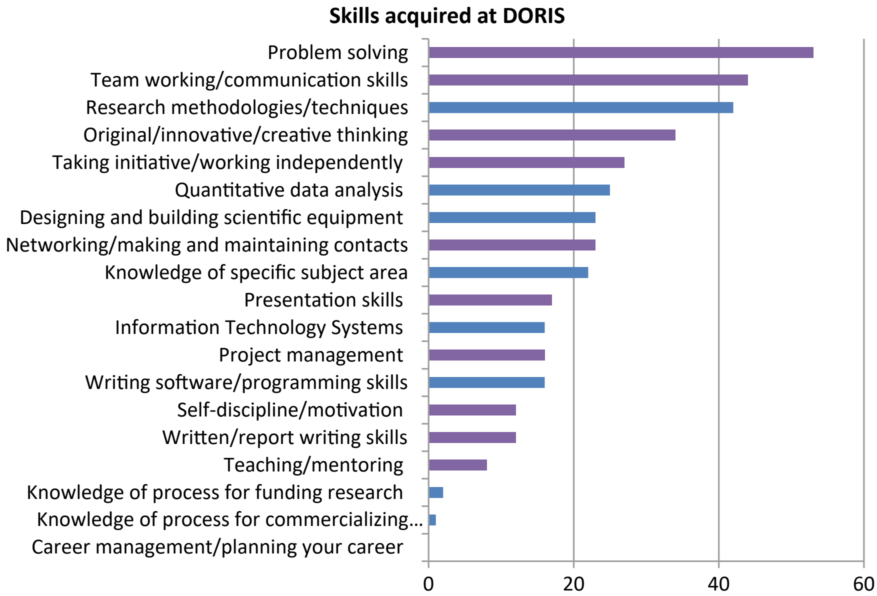

Fig. 2 Result of a survey of former Ph.D. students at DORIS on the rank of the skills acquired during their Ph.D. work that are seen useful for their current job. The horizontal axis is given in % of the respondents. Purple coloured bars indicate soft skills, blue coloured bars indicate knowledge-based skills. *Credits* S. Haid

indirect effects are generated: Since every supplier and subcontractor obtains certain inputs from other companies, there is an economic effect in the supply chain of every direct supplier. Furthermore, the induced effects capture the money flows, which are created by salaries, both directly at the facility and at other companies involved in the value chain. The induced effects can be put on a level with consumer spending of all employees, which are affected directly or indirectly by the facility's spending.

Even though the results of such analysis have to be taken with care—given a scarce data basis of 40 years of investments—it gives an impression of the benefits of the investment in DORIS for the region and which economic sectors profited most.

It is estimated that the overall DORIS investments throughout its 40 years of lifetime summed up to approximately 1.4 billion Euro (inflation-adjusted) including costs for (re)construction and operations. This number was derived by taking as an educated guess an appropriate fraction of the overall budget of DESY during the different phases of the lifetime of DORIS. However, third-party funding, especially from Universities invested in DORIS could be only partially tracked. The spending of the guest scientists is subject to assumptions as well: an approximation was done based on the number of scientists per year and a fixed amount of spending.

From the input–output-analysis we receive an indirect multiplier of 1.83 and an induced multiplier of 1.90. This means that one Euro spent on DORIS produces 0.83

€ sales volume through indirect effects and additionally 0.90 € through induced effects. The following box summarizes the short-term economic impact of DORIS:

Box 1
Short Term Economic Impact of DORIS

- Total budget spent (over DORIS life time): 1.4 bn €
- Direct Sales Effects: 700 M €
- Indirect Sales Effects: 590 M €
- Induced Sales Effects: 1.2 bn €
- Indirect (induced) Multiplier: 1.83 (1.9)
- Additional Jobs created in Germany: 12,500 FTE; which equals 300 FTE per year
- Effects in Hamburg: 200 direct jobs per year at DESY plus 450 Million Euro triggering about 1000 FTEs (= 25 FTE per year).

Even though the knowledge of these demand effects can help to gain political support, basic research is not and should not be regarded as a "business cycle" program to boost employment. The demand effects are socio-economic "side effects". The following effects on economic innovation reflect more the nature of research infrastructures like DORIS.

A large impact has been undoubtedly achieved through all those advancements in computer and network technology, and in electrical engineering, vacuum technology, radiology, and several other fields that have followed in the wake of the pushing of technical and scientific limits in accelerator and detector construction at DESY and other particle physics labs globally. Similarly, the collected global effort in advancing technologies and research in the area of synchrotron radiation has also led to advances that have had direct benefits in the development of more efficient batteries, LCD displays, and data storage devices in consumer electronics, enhanced and completely novel drug treatments, as well as software development, to name just a few.

d. Impact on the region

The regional impact of a research infrastructure is manifold. As described in the previous chapters, large scientific facilities and research labs have characteristic imprints on the regions which are hosting these facilities in terms of scientific output, higher education services, economic innovation, but also in terms of regional collaboration and networks. Moreover, research infrastructures often represent path-shaping investments and carry an institutional resilience that means continued and repeated investments in similar projects locally.

DORIS is a prime example for such structural socio-economic effects in the Hamburg metropolitan region. Already during or after the times of DORIS many other, and even larger science investments accompanied by the co-locations and aggregation of cooperating partner institutions and by auxiliary infrastructures followed—and all of them have made their own specific contributions to the local, regional, national and international economy.

- Research Infrastructures: Many experimental methods and technologies that were pioneered at DORIS have now become standards and led the way to further infrastructure investments. The continued improvements and the innovative atmosphere together with a remarkable collaborative spirit led later to the construction and operation of unique photon science infrastructures on the campus such as PETRA III, one of the most brilliant X-ray source in the world, and FLASH, the world's first free-electron laser in the X-ray range, and lastly the European XFEL as an international flagship facility for FEL science in the hard X-ray regime.
- Aggregation of Research Institutions: Already in 1975, EMBL established an outstation on the DESY campus to use the intense light for the investigation of biomolecules. In 1986, the MPG added another outstation at DORIS for three research group units followed by other external research organisations. The University of Hamburg has strongly increased the presence of its research institutions and interdisciplinary research centers on site and decided recently to also move the complete chemistry institutions to the campus.
- Interdisciplinary Centers: The concentration of world-leading research infrastructures and competences to decode the structure and dynamics of matter led to the establishment of further scientific and multidisciplinary institutions as collaborating platforms such as the Center for Free-Electron Laser Science (CFEL), the Centre for Structural Systems Biology (CSSB) and the Center for X-ray and Nano Science (CXNS).
- Innovation: Even if DORIS was not a major driver of innovation and transfer it is seen as a starting point for a further dynamic development with the recently opened start-up lab Bahrenfeld as a new place for hi-tech and science entrepreneurship and start-ups from the physical and bio sciences.

DORIS as a pioneering facility opened the way to the formation of new competence clusters on the campus, mainly in nano, bio, laser and engineering materials. This marked also the transition of the campus from a previously monodisciplinary site, into a science and innovation ecosystem with a rich and versatile multi-disciplinary landscape characterized by world leading research infrastructures, co-location of renowned research institutes and a stimulating innovation environment from which the Hamburg Metropolitan area greatly benefits today.

The development continues by the establishment of the so-called Science City Hamburg-Bahrenfeld, presently the largest and most ambitious future urban planning project of the City of Hamburg for the coming decades.

3 Ex-ante Consideration of the Socio-economic Impact of CTAO

While the societal benefits of DORIS—a single sited research facility in operation over a lifetime of more than 40 years—were discussed in the previous chapter, CTAO a facility in preparation and construction at four different sites will now be considered.

The Cherenkov Telescope Array Observatory (CTAO) will be the first ground-based gamma-ray observatory and the world's largest and most sensitive instrument for the detection of high-energy radiation. It will seek to address questions in and beyond astrophysics falling under three major themes: understanding the origin and role of relativistic cosmic particles; probing extreme environments; and exploring frontiers in physics. To achieve these goals, the CTAO is building two telescope arrays on two different sites: CTAO-North is located in the northern hemisphere at the Instituto de Astrofísica de Canarias' (IAC's) Roque de los Muchachos Observatory on La Palma (Spain), and CTAO-South is in the southern hemisphere near the European Southern Observatory's Paranal Observatory in the Atacama Desert (Chile). Moreover, the headquarters of the CTAO is hosted by Italy at the Instituto Nazionale di Astrofisica (INAF) in Bologna, and the Science Data Management Centre (SDMC).

Building on the concept of the broad societal benefits of research infrastructures, as demonstrated by the example of DORIS, the expected socio-economic impact of CTAO is outlined below along four dimensions: Science, Business, Region and Public (Fig. 3).

Science

CTAO addresses science questions across disciplines: not only in astrophysics but also in cosmology and particle physics, and in connection to environmental sciences—relevant, since the Earth's atmosphere is an integral part of the 'detector' and light pollution, and atmospheric conditions impact the quality of detection. CTAO is expected to revolutionize astronomy at the highest energies of the spectrum, regarding

- the understanding of cosmic particle accelerators and the impact of the high-energy particles on their environment and on cosmic evolution;
- the understanding of extreme environments in the Cosmos, such as the vicinity of neutron stars and black holes, but also of the radiation fields and magnetic fields permeating the giant cosmic voids;
- and the understanding of how the Universe behaves at the most basic level (fundamental physics), such as the nature of dark matter, the existence of axion-like particle and deviations from Einstein's theory of special relativity.

The CTAO will be constructed and operated to serve the needs of a broad scientific community where individual parties share their knowledge and capacities to enable scientific research that is impossible without such a research consortium. Currently

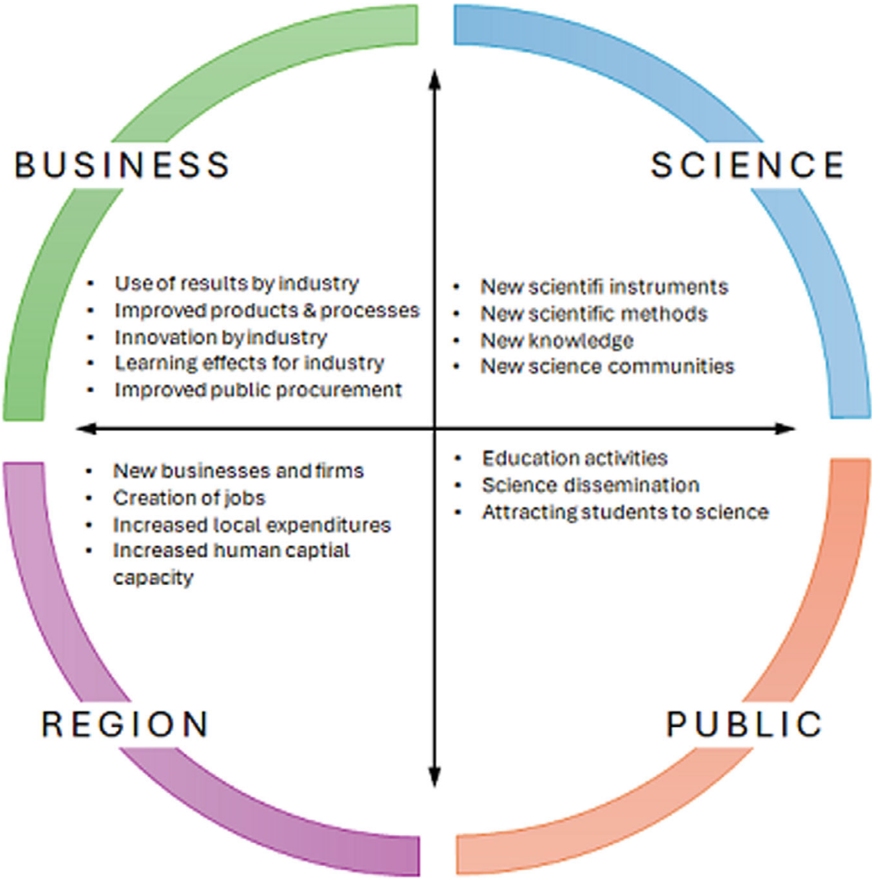

Fig. 3 Illustration of the socio-economic impact dimensions of CTAO. *Credits* S. Haid

about 1500 members from more than 150 institutes in 25 countries are organized within the CTA consortium (CTAC).

Business

The CTAO Construction Project contributes to raising the technological level of European industry and Small and Medium Enterprises, thus improving the competitive position through their involvement in RI development and service provision.

It includes in its design a range of technical innovations, many of which are being developed in cooperation with SMEs as part of the Preparatory Phase, and relying on the SMEs for production of instrument components.

Region

Large-scale scientific installations intrinsically shape the region where they are located and as such, they are important not only as contributors to competitiveness, but also promote the engagement between science and society.

The most important asset for a RI is, arguably, its human capital. This includes its own staff that builds and operates the facility together with the In-kind contribution (IKC) teams from partner institutions as well as the user community who exploits it for research. CTAO will play an important role in capacity building. Young researchers and technical personnel will be trained at this research instrument and gain knowledge that goes beyond scientific methods and techniques. Above all, they will learn how to work in international and interdisciplinary teams on innovative solutions for complex questions. Most likely, the development of this enormous work force of skilled people for the industry will be the largest economic impact that CTAO will on its four different sites.

Public

Research Infrastructures also have a tremendous impact on skills and education agendas irrespective of their size. Through their outreach to students, the general public and other key stakeholders, they steadily improve the perception and understanding of science and technology in society at large. It is the goal of the CTAO to enhance the attractiveness of the research profession at earlier education stages (high school) and to guarantee high-impact quality education in undergraduate students, with the aim of helping prepare potential future workers and science users of the Observatory.

It will also reinforce the partnership between the European Commission, member states and associate countries in establishing a pan-European Research Infrastructure. It includes a wide range of stakeholders from the Americas, Africa, Asia and Australia, promoting world-wide cooperation, linking the worldwide science community and representing a global research infrastructure.

4 Conclusion

The case study of DORIS very impressively demonstrates that a major scientific facility can be continuously adjusted and upgraded to meet the changing requirements in science. DORIS went through various phases and different scientific missions, showing that the facility and its related services was sustainably utilized over many decades. The facility has been a pioneer in several ways: in accelerator science and technology, in particle physics and, most prominently, in photon and life sciences. It paved the way towards modern colliders and 3rd generation SR machines and developed numerous methods and instrumentation that are now being used worldwide.

This transformation of the campus triggered by research at DORIS had and still has a significant impact on the regional development of the larger Hamburg metropolitan area. Not only that the demand effects of the major financial investments in the construction and operation of research infrastructures that followed DORIS such as PETRA III, FLASH and European XFEL generated a large economic impact, but also the multi-disciplinary research at DORIS was the origin of the formation of new competence clusters, the begin of an aggregation of research institutes and the start of the growth of an innovation ecosystem on campus.

Finally, DORIS played and CTAO already plays an important role in capacity building. Young researchers and technical personnel are trained at research instruments and gain knowledge that goes beyond scientific methods and techniques. Above all, they learn how to work in international and interdisciplinary teams on innovative solutions for complex questions.

During the analysis of the case of DORIS it has quickly become clear that the separation of one research infrastructure from the rest of the research center DESY and often from the whole environment of research organizations, universities and other research infrastructures is hardly possible. The impacts are often not only linked to one but to a variety of research infrastructures and instruments. It is the collaboration between these multiple actors around research infrastructures and the open access to these tools that generates their enormous added value for society.

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