WORLD ECONOMY RESEARCH INSTITUTE

INCREASING EUROPEAN INNOVATION POTENTIAL THROUGH COMMON INVESTMENTS IN PRIORITY RESEARCH INFRASTRUCTURES

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INTRODUCTION

The aim of this study is to investigate the rationale, activities and theoretical background for analysing the role of common EU investments in priority research infrastructures for increasing European innovation potential. Research Infrastructures are at the core of the knowledge triangle of research, education and innovation. By offering access to high quality services to researchers from different countries, they assemble a critical mass of people, knowledge and investment, facilitating international cooperation in science. Therefore, constructing the priority European Research Infrastructures is one of the most important steps in realizing the European Research Area. Internationalized research infrastructures provide the platforms, which bring together knowledge, human and other resources, from wherever they are located, to address research issues that cannot be tackled by single country or region alone.

According to the conceptual framework of the study, the impact of common EU investments in priority research infrastructures on solving the problems with fragmentation and insufficient cooperation between researchers in Europe is analysed in the perspective of three concepts: social capital, innovation system and economic networks. They provide explanation for the need of pooling resources, and partnership in constructing European priority research infrastructures. According to these theoretical concepts, common EU investments have an impact on increased cooperation and raising resources needed for key research infrastructures, leading to higher knowledge creation and technological advancement of the economy, consequently resulting in greater productivity, and finally contributing to faster economic growth.

This study is structured as follows. In the first part, definitions, basic futures, benefits and typology of research infrastructures are presented, together with the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap, which identifies new research infrastructures corresponding to the long term needs of the European research communities. In the second section, the problems connected with current state of the development of research infrastructures in Europe are identified and analysed, mainly: fragmentation of European investments, high complexity of research infrastructures, connected with e.g. increasing capital-intensity and technical sophistication of modern research, as well as the need to solve key societal challenges, which in many cases are addressed by research infrastructures. The third part of the study starts with an introduction to the new institutional economics approach proposed by O.E. Williamson, which forms the theoretical background useful in analysing an impact of research infrastructures. This concept enables to investigate such an impact at four levels of social analysis: embeddedness, institutional environment, governance, and resource allocation. Next, the most important economic theories that help to explain the main impact areas of European Research Infrastructures are analysed, like: social capital theory, the concepts of innovative milieu and creative class, innovation systems theory and economics of network theory. The forth part of the study focuses on the review of possible indicators that may be used in measuring the impacts of research infrastructures, as well as it contains statistical analysis of financial statistical data on allocation of funds to the projects implemented by RI in the framework of FP7 and Horizon 2020 programs (part INFRA).

1. Definition, typology and characteristics of research infrastructures

1.1 Definition of research infrastructures

There is no single definition of research infrastructure in the literature. One of the definitions is given in the Community legal framework for a European Research Infrastructure Consortium (ERIC) regulation[1], which says that research infrastructure "means facilities, resources and related services that are used by the scientific community to conduct top-level research in their respective fields and covers major scientific equipment or sets of instruments; knowledge-based resources such as collections, archives or structures for scientific information; enabling Information and Communications Technology-based infrastructures such as Grid computing, software and communication, or any other entity of a unique nature essential to achieve excellence in research".

On the other hand, in a press release to celebrate the 10th anniversary of the ESFRI Roadmap[2], the European Commission stated that "the term "research infrastructures" refers to facilities, resources and related services used by the scientific community to conduct top-level research in their respective fields, ranging from social sciences to astronomy, genomics to nanotechnologies".

In the European Parliament and the Council of the European Union Regulation on Horizon 2020[3], research infrastructures were defined as "facilities, resources and services that are used by the research communities to conduct research and foster innovation in their fields. They include: major scientific equipment (or sets of instruments), knowledge-based resources such as collections, archives and scientific data, e-infrastructures, such as data and computing systems and communication networks and any other tools that are essential to achieve excellence in research and innovation".

Considering existing definitions, shorter description is provided by MERIL (Mapping of the European Research Infrastructure Landscape) team, according to which "a European Research Infrastructure is a facility or (virtual) platform that provides the scientific community with resources and services to conduct top-level research in their respective fields"[4].

The above definitions of research infrastructures underline mostly their material nature and physical component, however, S. Anderson[5] postulates that we should move away from the long view focus on infrastructure as a 'thing' to be 'built' to a perception of research infrastructure as "part of a process of change, collaboration, and engagement". Consequently, if infrastructure is a basically relational concept, it may be the right question to ask: "when" – not "what" – is an infrastructure[6]. Hence, we may say that there is a real research infrastructure when it becomes dynamic not static, and operates as an innovation ecosystem, in which different elements interact and move in a continuous process of engagement, adjustment, and readjustment.

1.2 European research infrastructures – basic futures and benefits

The significance of research infrastructures has been increasing. In almost all areas of science, they have become indispensable for solving scientific problems and looking for the answers to research

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[1] Council Regulation (EC) No 723/2009 of 25 June 2009 on the Community legal framework for a European Research Infrastructure Consortium (ERIC), Official Journal of the European Union 52 (8 August 2009).

[2] European Commission (2012), *MEMO. ESFRI: research infrastructures for Europe*, Brussels, 10 October 2012, http://europa.eu/rapid/press-release_MEMO-12-772_en.pdf [last accessed: 13 July 2015].

[3] Regulation (EU) No 1291/2013 of the European Parliament and of the Council of 11 December 2013 establishing Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020) and repealing Decision No 1982/2006/EC (1), Article 2 (6), Official Journal of the European Union, L 347/104.

[4] MERIL (2011), Research Infrastructures of European relevance. A comprehensive inventory, European Science Foundation.

[5] S. Anderson (2013), "What are Research Infrastructures?", *International Journal of Humanities and Arts Computing,* Vol.7, No.1-2, pp. 4–23.

[6] S.L. Star, K. Ruhleder (1996), "Steps toward an ecology of infrastructure: design and access for large information spaces", *Information Systems Research,* Vol.7, No.1, pp. 111–134.

questions[7]. According to the MERIL (Mapping of the European Research Infrastructure Landscape) team, the research infrastructure should[8]:

- offer access to scientific users from Europe and beyond through a transparent selection process on the basis of excellence,
- offer top quality scientific and technological performance, that should be recognized as being of European relevance,
- have stable and effective management.

At the macro-level, a number of broad categories of offerings of research infrastructures can be identified, like access to: data and physical/analogue objects, services, expertise, and laboratory facilities[9]. In practice, research infrastructures may fulfil different functions. For example, some of them aim to create critical mass for actual research activities in certain areas, whereas others aim to provide unique research services to users from different countries[10]. According to OECD, there are various possible types of added value from research infrastructures, notably[11]:

- scientific (e.g. developing new equipment, setting common standards and formats),
- operational (e.g. speeding up the research, avoiding duplication of actions),
- educational (e.g. Ph.D. programs),
- economic (in the form of technology transfer to the public or private sectors),
- political (e.g. strengthening regional integration, providing the scientific underpinning to an international treaty).

Although research infrastructures usually develop to respond to the needs of specific research communities, strong cooperation between different research infrastructures is needed to serve the trans-boundary research and to explore scientific questions at the intersection of different fields of science. Hence, RI are the solutions to conduct joint research projects and develop concepts, devices, and methods that can be used to integrate knowledge[12]. Research infrastructures constitute an important element of innovations system not only in the EU, but also in developing countries. For example, the study published in 2016 by Qiao, Mu, Chen[13] proved that research infrastructures not only have promoted scientific advancements in many disciplines in China, but also they are important to the acquisition of new knowledge, and contribute to the propagation of competitive scientific organizations and scientific talent. In addition, networking and clustering impacts are important scientific effects of research infrastructures, as they increase the effectiveness of scientific activities in China.

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[7] The German Council of Science and Humanities (Wissenschaftsrat) (2013), *Science-driven Evaluation of Large Research Infrastructures for the National Roadmap – Pilot Phase*, Background Information, Berlin.

[8] European Science Foundation (2013), Research Infrastructures in the European Research Area. A report by the ESF Member Organisation Forum on Research Infrastructures, European Science Foundation (ESF), Strasbourg, p. 10-11.

[9] European Science Foundation (2011), *Research Infrastructures in the Digital Humanities*, Science Policy Briefing No 42, p. 6.

[10] T. Stahlecker, H. Kroll (2013), *Policies to Build Research Infrastructures in Europe – Following Traditions or Building New Momentum?*, Fraunhofer Institute for Systems and Innovation Research ISI Competence Center "Policy and Regions", Working Papers Firms and Region No. R4/2013, Karlsruhe, p. 9.

[11] OECD (2014), *International Distributed Research Infrastructures: Issues and Options*, Organisation for Economic Co-operation and Development, p. 8.

[12] S. Sorvari, W. Kutsch, P. Laj, A. Asmi, M. Brus (2016), *ENVRI Cluster-a community-driven platform of European environmental research infrastructures for providing common solution for science and society*, in: EGU General Assembly Conference Abstracts, Vol. 18, p. 15226.

[13] Qiao L., Mu R., Chen K. (2016), "Scientific effects of large research infrastructures in China", *Technological Forecasting and Social Change*.

1.3 Types of European research infrastructures

The most common types of research infrastructures are:

1. 'Single-sited' research infrastructures – a single resource at a single location.

Single-sited research infrastructures are usually large scale facilities, which creation is strongly associated with construction works, large buildings and extremely expensive equipment. The location of new single-sited research infrastructure is often a compromise between scientific, economic and political factors, as it requires long-term planning and can be established only with high-level political and financial support. However, the high visibility of large facilities to the general public makes it also attractive for politicians to support them. In many cases, institutional, centralized funding allows large single-sited research infrastructures to offer access and service to external users free of charge. This type of facilities are mostly known from the field of physics, including astronomy[14]. One of the most famous example is the European Organization for Nuclear Research (CERN), the world's largest particle physics laboratory.

2. 'Distributed' research infrastructures – a network of distributed resources.

This type of infrastructure is referred to by OECD[15] as an International Distributed Research Infrastructure (IDRIS), defined as "a multi-national association of geographically-separated distinct entities that jointly perform, facilitate or sponsor basic or applied scientific research". Distributed research infrastructures are usually smaller than single-sited, large research facilities, and may have a "lighter" administrative structure. The location for central facility and headquarters is selected based on scientific, financial and political considerations. Due to its inherently distributed nature, efficiency of co-ordination is a crucial requirement. The central staff may be located in a single location (central facility), several locations (when there is shared central responsibility between different partners) or the staff may be distributed among all of the different partners (in case of highly distributed research activities). An example of distributed research infrastructures are: the European Mouse Mutant Archive (EMMA), Global Earth Observation system of systems (GEOSS) or International Cancer Genome Consortium (ICGC).

3. 'Virtual' research infrastructures – the service is provided electronically

Virtual research infrastructures are the most commonly found in social sciences, computer and data treatment, as well humanities. Their examples are: databases, archives, etc. that can be used by researches from their own workstations. This allows new forms of cooperation among scientists, who may work together, regardless of their location[16]. An example of virtual research infrastructure is the GÉANT high-speed network (e-Infrastructure initiative launched to facilitate cooperation among researchers).

The view on how common in practice the above-mentioned types of research infrastructures occur is given by the results of a survey research conducted from March 2006 to March 2007 on 598 organisations by the European Commission (The Research Infrastructures unit within DG Research)

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[14] ERA-Instruments (2010), Mid-Size Instrumentation in the Life Sciences: III. Development of Research Infrastructures in Europe, Brandt GmbH, Druckerei und Verlag, Bonn.

[15] OECD (2014), *International Distributed Research Infrastructures: Issues and Options*, Organisation for Economic Co-operation and Development, p. 7.

[16] Federal Ministry of Education and Research (2013), *Research Infrastructures for the Humanities and Social Sciences*, Bonn, p. 3.

and European Science Foundation[17]. It should be noted that the sample is much broader then European priority infrastructures only; the aim of presenting these statistics is to provide a general overview on the prevalence of different types of research infrastructures (that may vary in scale, starting e.g. from simple digital library) in different areas of science. As it can be seen from Table 1, most of the research infrastructures (63%) were single-sited, 25% were working as distributed facilities, and only 12% were virtual. However, the nature of the research infrastructures differed strongly according to the field of research in question. For example, in the area of energy a large majority of research infrastructures remain single-site laboratories (96%), whereas the opposite was true for the social sciences, where virtual networks (42%) dominate.

Table 1. Scientific fields and organisational features of research infrastructures

The field of research	single-site	distributed/ co-operative	virtual
Social Sciences	32%	26%	42%
Computer and Data Treatment	48%	24%	28%
Humanities	52%	23%	25%
Biomedical and Life Sciences	60%	27%	13%
Environmental, Marine and Earth Sciences	50%	38%	12%
Nuclear and Particle Physics, Astronomy, Astrophysics	74%	18%	8%
Engineering	68%	26%	6%
Energy	96%	none	4%
Material Sciences	89%	10%	1%
Total	63%	25%	12%

Source: European Commission/European Science Foundation (2007), *Trends in European Research Infrastructures, Analysis of data from the 2006/2007 survey*, https://ec.europa.eu/research/infrastructures/pdf/survey-report-july-2007_en.pdf#view=fit&pagemode=none [last accessed: 14 July 2016]

1.4 European Roadmap for ESFRI

The important phase in the realization of large research infrastructures is roadmapping, which may be understood as systematic strategic planning. The term "roadmap" was adopted by the OECD Global Science Forum (GSF)[18], which identified two principal actors/stakeholders in a roadmapping process: the scientific community and the governmental authorities (especially funding agency officials). The key role of the scientists is restricted to scientific arguments, aimed at defining the research questions, and identifying a corresponding optimal set of high-priority research infrastructures. On the other hand, policymakers must often introduce non-scientific issues and priorities into the roadmapping process, including social, political and economic priorities, for example linking research infrastructures to innovation, economic competitiveness, and job creation.

The European Strategy Forum on Research Infrastructures (ESFRI) Roadmap identifies new research

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[17] European Commission/European Science Foundation (2007), *Trends in European Research Infrastructures, Analysis of data from the 2006/2007 survey*, https://ec.europa.eu/research/infrastructures/pdf/survey-report-july-2007_en.pdf#view=fit&pagemode=none [last accessed: 14 July 2015].

[18] OECD Global Science Forum (2008), *Report on Roadmapping of Large Research Infrastructures*, http://www.oecd.org/sti/sci-tech/47057832.pdf [last accessed: 17 July 2015].

infrastructures corresponding to the long term needs of the European research communities, covering all scientific areas, regardless of possible location. ESFRI got the mandate from the Competitiveness Council in 2004 to develop a roadmap for research infrastructures in Europe. The first roadmap from 2006 included 35 new research infrastructures or major upgrade of existing ones. Since this time, there were three ESFRI roadmaps updates in 2008, 2010, and 2016. In respect to the ESFRI Roadmap 2016, it contains both the interim evaluation of the existing projects and the ex-ante evaluation of the new proposals that were selected as new entries[19]. Identified research infrastructures are characterized by different degrees of maturity, but they are usually supported by a relevant European partnership or intergovernmental research organization. A growing number of countries have prepared national roadmaps that establish the prioritization of national and pan-European research infrastructures, using the ESFRI Roadmap as a reference. This is taken into account when defining national budgets, which ensures long-term financial commitment[20].

2. The rationale for common EU investments in priority research infrastructures

2.1 Fragmentation of European investments in research infrastructure

One of the biggest obstacles for restoring the EU leadership position in science and technology is the fragmentation of research policy, which is carried out by the European Commission and 28 member states. This explains the heterogeneous innovation performances across Europe and the difficulties in organizing holistic approaches at the European level[21]. T. Stahlecker and H. Kroll[22] confirm that one of the main reasons why continuously developed European Research Area is still far from acting as supra-national innovation system (in which research infrastructures would constitute the important elements integrating citizens from different member states) is fragmented political landscape in research policy, with national governments reluctant to yield more control and budget to the European level. Another problem is that the networks of co-operation and human capital exchange are pre-defined by national boundaries, as according to K. Pavitt, P. Patel[23] innovative activities are greatly influenced by national systems of innovation in terms of: the quality of basic research, workforce skills, the degree of competitive rivalry, systems of corporate governance, and local inducement mechanisms.

Tremendous fragmentation of the European research infrastructures leads to the lack of transparency and duplication of their objectives and actions[24]. T. Stahlecker and H. Kroll[25] noticed that although many European scientific units have a long tradition of excellence, when driving progress in numerous

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[19] European Strategic Forum for Research Infrastructures (ESFRI) (2016), *Strategy Report on Research Infrastructures. Roadmap 2016*, Science and Technology Facilities Council.

[20] B. Warneck (2014), *Workshop to Launch the ESFRI Roadmap 2016 – Report*, http://www.copori.eu/_media/Report-final_28-10-14.pdf [last accessed: 17 July 2015].

[21] A. Sartori, L. Berlinguer (2013), *European Research Area. Towards a Maastricht for research*, https://www.researchitaly.it/uploads/7892/Maastricht_ricerca.pdf?v=3d1930a [last accessed: 28 July 2015]

[22] T. Stahlecker, H. Kroll (2013), *Policies to Build Research Infrastructures in Europe – Following Traditions or Building New Momentum?*, Fraunhofer Institute for Systems and Innovation Research ISI Competence Center "Policy and Regions", Working Papers Firms and Region No. R4/2013, Karlsruhe.

[23] K. Pavitt, P. Patel (1999), *Global corporations and national systems of innovation: Who dominates whom?*, in: D. Archibugi, J. Howells, J. Michie (eds.), Innovation Policy in a Global *Economy*, Cambridge: Cambridge University Press, pp. 94-119.

[24] Committee for Research Structure of the Royal Swedish Academy of Sciences (2012), *Transnational Coordination of European Research Infrastructures*, The Royal Swedish Academy of Sciences, Stockholm.

[25] T. Stahlecker, H. Kroll (2013), *Policies to Build Research Infrastructures in Europe – Following Traditions or Building New Momentum?*, Fraunhofer Institute for Systems and Innovation Research ISI Competence Center "Policy and Regions", Working Papers Firms and Region No. R4/2013, Karlsruhe.

key areas of science, the persistent national fragmentation of investments prevents created infrastructures to reach a certain critical mass. The understanding of a need for certain critical mass should not be limited only to a technical level. Fragmentation of European research infrastructures creates also problems with sufficient financing, as the cost of implementation of single investment projects often exceeds the funding capacity of individual countries. The problem is even bigger when taking into account insufficient transnational cooperation between the existing research units of sub-critical size. Moreover, as learning is a cumulative process, all research teams benefit from the increase in diversity and the broadening of the knowledge base[26], and this is lacking in research infrastructures fragmented across member countries.

2.2 High complexity (scale and costs) of European research infrastructures

One of the rationale for pooling the resources across Europe to build and operate research infrastructures is their increasing complexity, scale and costs. In the context of scarce public resources, it is an important step in European research and innovation policy to catalyse investments in major infrastructures, which are given political priority and for which new funding mechanisms are being developed[27]. In fact, increasing complexity and costs of research infrastructures makes international collaboration and coordination in that area a necessity. Therefore, transnational cooperation is seen as essential to reach and maintain a competitive level in research.

The increasing capital-intensity of modern research is connected with rapid evolution of science, where more and more sophisticated and powerful experimental instruments need to be designed and constructed in order to back such a progress and push forward the frontiers of knowledge. Large scale scientific projects tend to entail substantial investment costs related to the design and construction of research infrastructures, which often rise considerably from the ex-ante estimates. The growing number of research infrastructures financed and their increasing average cost call for a responsible decision-making when deciding if to spend considerable amounts of public money[28]. Setting-up, or modernising, research infrastructures usually requires a substantial level of financial investment and a long-term investment and operation strategy. This strategy entails careful planning of the operation phase and possible future reinvestments. This involves the purchase of technologically advanced equipment, clustering of specific skills and devising appropriate governance structures[29].

In order to resolve the complexity and resulting weaknesses of the European research infrastructures, the report of the Committee for Research Structure of the Royal Swedish Academy of Sciences[30] suggested that all these infrastructures should be restructured and reorganized by using an objective evaluation, including impact analysis and cost-benefit studies. In evaluation, a clear and transparent definition of efficiency needs to be elaborated, by covering two aspects: the efficiency in producing knowledge and the efficiency in its commercialisation. Moreover, research infrastructures should be listed and divided into different areas, defined by their scientific or technological objectives, in order

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[26] P. Cooke (2002), Knowledge economies: Clusters, learning and cooperative advantage, Routledge.

[27] European Commission (2010), Communication from the Commission to the European Parliament, the council, the European Economic and Social Committee and the Committee of the Regions, *Europe 2020. Flagship Initiative. Innovation Union*, COM(2010) 546 final, SEC(2010) 1161, Brussels, 6.10.2010.

[28] M. Florio, E. Sirtori (2014), "The Evaluation of Research Infrastructures: a Cost-Benefit Analysis Framework", Departmental Working Papers 2014-10, Department of Economics, Management and Quantitative Methods at Università degli Studi di Milano.

[29] E. Griniece, A. Reid, J. Angelis (2015), Guide to Evaluating and Monitoring Socio-Economic Impact of Investment in Research Infrastructures, Technopolis Group, Tallinn.

[30] Committee for Research Structure of the Royal Swedish Academy of Sciences (2012), *Transnational Coordination of European Research Infrastructures*, The Royal Swedish Academy of Sciences, Stockholm.

identify and eliminate fragmentations and duplications. An example of innovative cost–benefit analysis framework that has been used to assess the impact of an applied research infrastructure is presented in an article published in 2016 by Battistoni *et al*[31]. Another type of costs are different types of external costs (negative externalities), for example connected with environmental degradation, which should be taken into account while aiming for sustainable development[32].

Research infrastructures represent important supporting pillar of the research system. Along with their scientific importance also the challenges grow: financially, because they become more and more resource-intensive, and with respect to the organization, because the degree of complexity of the institutions or the networks increases[33]. A critical ingredient of any infrastructure is high capital intensity. According to M. Florio and E. Sirtori[34], capital fixed expenditure overcomes operating costs and is a large fraction of the total present value of project cost. This is particularly true in so called Big Science, which is performed using some of the most expensive equipment. However, ERA-Instruments publication[35] states that two necessary key factors for research infrastructures are operation costs and personnel. This view is confirmed by facility managers who consider purchase of equipment in many cases not as the major bottleneck for research infrastructures. The real limiting factors are: the costs for operation, maintenance and upgrades, and costs for personnel running equipment and increasingly for processing data.

2.3 The complexity of realizing the projects in partnerships

Complexity generally refers to an emergent property of systems made of large numbers of self-organizing agents that interact in a dynamic and non- linear fashion and share a path dependent history[36]. Increasing complexity of scientific processes makes partnership a key success factor for research infrastructures, which need to pool people and resources in order to achieve technological critical mass. However, usually research teams face different types of difficulties in pooling and sharing knowledge. The complexity of realizing the projects in partnerships is particularly high in case of interdisciplinary or international collaboration. Interdisciplinary teams face particular challenges around their lack of redundancy in disciplinary coverage and their lack of a shared base of domain and procedural knowledge. Such groups depend on their members, who represent different sub-disciplines and bring knowledge to the team's work. Consequently, those from other disciplines must be open to hearing and incorporating such knowledge. To integrate and synthesize knowledge, the research team must be ready to engage together in contributing knowledge and learning from others. To bridge differences in disciplinary practice, research groups need infrastructures to support their joint work[37].

Despite the difficulties inherent in working in international and multilingual teams, EU funding for

[31] G. Battistoni, M. Genco, M. Marsilio, C. Pancotti, S. Rossi, S. Vignetti (2016), "Cost–benefit analysis of applied research infrastructure. Evidence from health care", *Technological Forecasting and Social Change*.

[32] Marcinkowski A. (2009), *Analiza kosztów zewnętrznych w służbie rozwoju zrównoważonego*, in: R. Grądzki, M. Matejun (eds), *Rozwój Zrównoważony – zarządzanie innowacjami ekologicznymi*, pp. 69-76.

[33] The German Council of Science and Humanities (Wissenschaftsrat) (2013), Science-driven Evaluation of Large Research Infrastructures for the National Roadmap – Pilot Phase, Background Information, Berlin.

[34] M. Florio, E. Sirtori (2014), "The Evaluation of Research Infrastructures: a Cost-Benefit Analysis Framework", Departmental Working Papers 2014-10, Department of Economics, Management and Quantitative Methods at Università degli Studi di Milano, p. 5.

[35] ERA-Instruments (2010), Mid-Size Instrumentation in the Life Sciences: III. Development of Research Infrastructures in Europe, Brandt GmbH, Druckerei und Verlag, Bonn, p. 15.

[36] P. Cilliers (1998), Complexity and Postmodernism: Understanding Complex Systems, Routledge, London.

[37] C. Haythornthwaite, K.J. Lunsford, G.C. Bowker, B. Bruce (2006), Challenges for research and practice in distributed, interdisciplinary, collaboration, in: C. Hine (ed.), New Infrastructures for Science Knowledge Production, Hershey, PA: Idea Group, pp. 143-166.

collaborative research, including research infrastructures, can stimulate the development of an international science teamwork model. In this model, individual researchers often serve as native informants, offering insider knowledge about the phenomena under study in their own countries. The single researcher can thus become part of a larger network, pooling information and broadening disciplinary perspectives. In this way, collaborative work produces synergy and helps to make sense of complexity and diversity[38].

2.4 Inherent technical complexity of the projects

Together with growing complexity of science and technology, the research infrastructure landscape becomes also increasingly more complex. In order to achieve technological critical mass, many large-scale facilities in Europe are financed jointly by the European Union and its member states. Increasing inherent technical complexity of the projects changes also the nature of research infrastructure, which come to be more digital and distributed. Modern science becomes extremely complex, and the research infrastructure landscape in Europe is diverse and multi-layered. Paradoxically, in some cases efforts to pool resources have added to the complexity, as large-scale EU-funded investments can combine several types of activities under one umbrella, networking different partner facilities and sub-projects. This growing complexity prevents research infrastructures in Europe from being exploited to their full potential. There is a high risk of both duplication of effort and neglect of gaps across the European Union[39].

The technical complexity of the research projects is also growing together with the rise of so called data-intensive science, also referred to as Linked Data, Big Data, or the 4th Paradigm[40], and other similar concepts. This new approach highlights the importance of investment into collecting and preparing massive amounts of data. Providing digital collection and preservation of research data is thus one of the key service that has to be provided by research infrastructures. Together with increasing complexity of research projects, the needs for preservation goes beyond just maintaining data accessible. Capturing and documenting the context of its creation and use requires sophisticated information networks. It is a massive task requiring to pool resources if European research infrastructure are to be able to capture and maintain usable series of data processing routines and modules. It is needed in order to establish the validity of scientific analysis, to repeat earlier computations on new data, and in general to make full use of the potential enrooted in data-intensive science[41].

2.5 The need to solve key societal challenges

According to the latest findings in economics, innovation goes beyond the technological and economic aspects, as it is a way of solving contemporary problems of development, such as the exclusion of some

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[38] L. Hantrais (2005), ”Combining methods: a key to understanding complexity in European societies?”, *European Societies*, Vol.7, No.3, pp. 399-421.

[39] European Science Foundation (2013), *The Research Infrastructure Information Base in Europe – Summary of the Roundtable Debate of 6 November 2013*, Brussels, http://www.esf.org/fileadmin/Public_documents/MERIL/Conf_summary_Dec13.pdf [last accessed: 17 July 2015].

[40] C. Bizer, T. Heath, T. Berners-Lee (2009), ”Linked Data – the story so far”, *International Journal on Semantic Web and Information Systems*, Vol.5, No.3, pp. 1–22.

[41] A. Rauber (2012), Digital Curation as a Key Component in Research Infrastructures: From Data Preservation to Processes Preservation and Verification, Proceedings of the 14th All-Russian Conference “Digital Libraries: Advanced Methods and Technologies, Digital Collections” – RCDL-2012, Pereslavl-Zalesskii, Russia, 15-18 October 2012.

groups from certain areas of socio-economic development and environmental protection issues[42]. The social dimension of innovation is also underlined by L. Kwieciński and A. Młodzińska-Granek, who indicate other mechanisms apart from high-tech innovative products that are critical for the development of a knowledge-based economy, like: social trust, willingness to cooperate, social creativity, and as interdisciplinary approach[43]. In recent years, there has been an increasing interest in solving the problems of modern societies, associated with so called Grand Challenges, like: ageing of society, mass urbanization, the growth of social inequalities, poverty, the tightening supply of energy, greenhouse gas emissions, environmental problems, migration, diseases of civilization, etc. Priority European research infrastructures may play an important role in finding innovative solutions to today's key societal challenges, as they constitute more permeable organizational structures, characterized by greater absorption capacity and engagement of various international actors. This modern approach to innovation, based on interactions and taking into account social needs, is reflected in the Open Social Innovation (OSI) paradigm, proposed by H. Chesbrough and A. Di Minin[44]. Open Social Innovation is defined by these economists as "the application of either inbound or outbound Open Innovation strategies, along with innovations in the associated business model of the organization, to social challenges". This paradigm is composed of two concepts: open innovation and social innovation, which in fact are not the same, but both ultimately strive for user-focused collaborative process[45]. D. Chalmers[46] expects that full implementation of the Open Innovation model will help to build a more porous organizational structures, characterized by greater absorption capacity and engaging various stakeholders in the social innovation processes. That is why priority European Research Infrastructures, which enable the cross-disciplinary, frontier research and innovation, are indispensable in tackling the Grand Challenges. By attracting and bringing together researchers, funding agencies, politicians and industry to act together and tackle the interdisciplinary scientific and technical issues of critical importance for the society, investments in infrastructures enable excellent research not being realizable without the access to these facilities due to a lack of capacities[47]. As part of the European Research Area, many of the priority European Research Infrastructures identified by ESFRI are already providing an environment supporting research to address the Grand Challenges in science, industry and society.

3. Theoretical background for analysing main areas of research infrastructures impact

An important theoretical background for analysing research infrastructures is provided by new institutional economics, which was developed, among others, by four Nobel laureates: Ronald Coase[48],

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[42] M.A. Weresa (2014), *Polityka innowacyjna*, Wydawnictwo Naukowe PWN, Warszawa, p. 18.

[43] L. Kwieciński, A. Młodzińska-Granek (2014), "Academic Entrepreneurship in the Humanities and Social Sciences: Research Conducted among Students of Wroclaw University", *Horyzonty Wychowania*, 13(26):33-49, p. 34.

[44] H. Chesbrough, A. Di Minin (2014), *Open Social Innovation*, in: H.W. Chesbrough, W. Vanhaverbeke, J. West (eds), *New Frontiers in Open Innovation*, Oxford University Press, Oxford, pp. 169-188.

[45] A.M. Kowalski (2015), *The Development of Social Innovation in Poland and Other EU Countries*, in: M.A. Weresa (ed.), *Poland: Competitiveness Report 2015. Innovation and Poland's Performance in 2007-2014*, Warsaw School of Economics – Publishing, Warsaw, pp. 261-280.

[46] D. Chalmers (2013), "Social innovation: An exploration of the barriers faced by innovating organizations in the social economy", *Local Economy*, Vol.28, No.1, pp. 17- 34.

[47] The European Strategy Forum for Research Infrastructures (ESFRI) (2011), *Strategy Report on Research Infrastructures. Roadmap 2010*, Luxembourg: Publications Office of the European Union.

[48] R. Coase (1998), "The New Institutional Economics", *American Economic Review*, 88(2), pp. 72-74.

Douglass North[49], Elinor Ostrom[50], and Oliver E. Williamson[51]. In particular, when applying the new institutional economics approach proposed by O.E. Williamson, we can observe an impact of common EU investments in priority research infrastructures at four levels of social analysis:

1) embeddedness, as partnerships developed around priority research infrastructures strengthen such informal institutions, like cooperation-friendly culture. However, these types of institutions change very slowly and are difficult if not impossible at all to be directly measured,
2) institutional environment, as formal rules of the game for research infrastructures in the EU are established, for example opening of Member-State-operated research infrastructures to full European user community, and the creation of new European priority research infrastructures, which may shape adaptive efficiency and change competition in science,
3) governance, e.g. coordination of programs' objectives for research infrastructures at the EU and national levels,
4) resource allocation, as the EU aims to catalyze investments in major infrastructures, which are given political priority and for which new funding mechanisms are being developed.

3.1 Social capital theory, innovative milieu, and the concept of creative class

One of the definition says that social capital is the sum of the resources, actual or virtual, that accrue to an individual or a group by virtue of possessing a durable network of more or less institutionalized relationships of mutual acquaintance and recognition[52]. The importance of this concept for research infrastructures is connected with the observation made by Putnam[53] and Adler and Kwon[54] that the social capital associated with the connections between external players lead to positive effects in raising resources (which are needed for capital intensive investments in RI) and building trust (which stimulates interactions) in the organization. Therefore, social capital provides links that facilitate the discovery of opportunities and the identification, collection and allocation of scarce resources within the organization[55], like research infrastructure. Similarly, J.S. Coleman[56] associates social capital also with ties between heterogeneous actors or different homogeneous networks that allow "the resources of one relationship to be appropriated for use in others", which has strong implications for European research infrastructures grouping international researchers in cross-disciplinary teams.

In the context of research activities, social capital refers to the stock of relationships, context, trust and norms that encourage suitable behavior for knowledge sharing[57], which includes cognitive and communication skills in a specific context[58]. Looking on the research infrastructures through a prism

[49] D.C. North (1990), *Institutions, Institutional Change and Economic Performance*, Cambridge University Press.
[50] E. Ostrom (1990), *Governing the Commons: The Evolution of Institutions for Collective Action*, Cambridge University Press, Cambridge, UK.
[51] O.E. Williamson (2000), "The New Institutional Economics: Taking Stock, Looking Ahead", *Journal of Economic Literature*, Vol.38, No3, pp. 595-613.
[52] P. Bourdieu, L. Wacquant (1992), *An Invitation to Reflexive Sociology*, Chicago: University of Chicago Press, p. 119.
[53] R. Putnam (2000), Bowling Alone: The Collapse and Revival of American Community, Simon & Schuster, New York, NY.
[54] P. Adler, S. Kwon (2002), "Social capital: prospects for a new concept", *Academy of Management Review*, Vol.27, pp. 17-40.
[55]P. Greene, T. Brown (1997), "Resource needs and the dynamic capitalism typology", *Journal of Business Venturing*, Vol.12, pp. 161-173.
[56] J.S. Coleman (1988), "Social capital in the creation of human capital", *American Journal of Sociology*, Vol.94 (supplement), pp. S95-S120 (p. S109).
[57] P. Anklam (2002), "Knowledge management: the collaboration thread", *Bulletin of the American Society for Information Science and Technology*, Vol.28, No. 6, pp. 1-8.
[58] G. Widén-Wulff, M. Ginman (2004), "Explaining knowledge sharing in organizations through the dimensions of social capital", *Journal of Information Science*, Vol.30, No.5, pp. 448-458.

of network organizations, social capital may be considered as "the resources gained from participating in relationships networks which are relatively institutionalized"[59]. This identifies the economic or other advantages of people's socially embedded interaction that may take place in knowledge organizations. On the other hand, social capital may be considered as the fundamental basis for functioning of research infrastructures, as according to F. Fukuyama[60] it refers to underlying forces, which trigger interactions: "social capital is an instantiated informal norm that promotes cooperation between two or more individuals".

An analysis of the socio-economic impact of African-European research infrastructure cooperation[61] showed that a major benefit of many research infrastructures is the build-up of social capital. It is created through meaningful interactions between people and therefore facilitates sustainable learning and use of skills and knowledge. Broadly understood as the institutions, relationships, attitudes, and values that govern interactions among people and contribute to economic and social development, it refers to the benefits that arise from networks, relations and mutual trust. Examples of positive impact of research infrastructures on social capital include benefits from the inflow of highly skilled professionals through visits of foreign scientists and the knowledge exchange, which stimulates diversity and creativity and leads to innovative and creative ideas. Moreover, research infrastructures provide an entry point for young scientists into networks of knowledge, expertise, and practice.

The notion of social capital shares some similarities (mainly focus on the importance of socially embedded collaboration for innovation driven regional development) with the concept of innovative milieu[62], defined as "the set, or the complex network of mainly informal social relationships on a limited geographical area, often determining a specific external 'image' and a specific internal 'representation' and sense of belonging, which enhance the local innovative capability through synergetic and collective learning processes"[63]. One of the attempts to use innovative milieu concept to consider the role of research infrastructures was made by L. Scaringella, and J.J. Chanaron in the article published in 2016[64]. The milieu approach mainly tries to analyses and explain how a good regional institutional endowment in terms of networked universities, research laboratories, public support institutions and firms, can lead to higher innovativeness of the regional economy. However, it seems that the concept of innovative milieu is somehow constrained mainly to local and regional context and therefore has limited applications to analyze international cooperation in the framework of European research infrastructures.

Another concept strongly related with social capital is the concept of creative class, which consists of two subgroups[65]:

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[59] R. Landry, N. Amara, M. Lamari (2001), "Social capital, innovation and public policy", *ISUMA – Canadian Journal of Policy Research*, Vol.2, pp. 73-79 (p. 74).

[60] F. Fukuyama (2000), *Social Capital and Civil Society*, IMF Working Paper WP/00/74, Washington DC: International Monetary Fund, p. 3.

[61] Promoting African European Research Infrastructure Partnerships (2012), *An Analysis of the socio-economic impact of African-European research infrastructure cooperation*, PAERIP, http://www.paerip.org/sites/www.paerip.org/files/PAERIP%20report%203.3%2015092012.pdf [last accessed: 21 July 2015].

[62] M. Fromhold-Eisebith (2004), "Innovative Milieu and Social Capital", *European Planning Studies*, Vol.12, No.6, pp. 747-765.

[63] R. Camagni (1991), Introduction: from the local 'milieu' to innovation through cooperation networks, in: R. Camagni (ed.), Innovation Networks: Spatial Perspectives, London: Belhaven Press, pp. 1-9 (p.3).

[64] L. Scaringella, J.J. Chanaron (2016), "Grenoble–GIANT Territorial Innovation Models: Are investments in research infrastructures worthwhile?", *Technological Forecasting and Social Change*.

[65] R. Florida (2002), The Rise of the Creative Class: And How it's transforming work, leisure, community and everyday life, New York: Perseus Book Group.

1) super-creative core (including occupations in e.g. science, engineering, education, computer programming, research), which is fully engaged not only in problem solving, but also problem finding,
2) creative professionals, who work in a wide spectrum of knowledge- intensive industries, like the high-tech sector or business management.

An important finding of R. Florida is that members of the creative class tend to settle in certain places, called creative regions, which according to 3T´s model are characterized by high levels of: technology, talent and tolerance[66]. This concept has its implication for research infrastructures, as they are the centers, in which creative class is deeply rooted. Individuals working in research infrastructures fully engage in the creative process and develop new concepts, subsequently resulting in new products and economic growth.

3.2 Innovation systems theory

Simple linear models of innovation process, which were the first attempt to illustrate how innovation is created, do not cover fully the entire spectrum of factors influencing the development and implementation of technology. Their weakness is that they do not explain differences in innovation processes in different countries and regions, some of which are innovation leaders while others remain imitators. Numerous comparative analysis of innovation processes in individual economies and sectors led to the perception of the innovation system[67]. This is a non-linear perspective emphasizing interdependences and interactions between the elements of the system, as well as interactive learning[68]. The concept of innovation system was initiated by C. Freeman[69] and further developed by other economists, who were focusing on different dimensions, distinguishing for example: national systems of innovation (B.Å. Lundvall[70], C. Freeman[71]),; regional and local systems of innovation (P. Cooke[72]); sectoral systems of innovation (F. Malerba[73]), or technological systems of innovation (B. Carlsson, R. Stankiewicz[74]). Study on European research infrastructures shows that they can play a special role in another, new type of innovation system, which may be called supra-national system of innovation, represented by the emerging European Research Area[75].

A special contribution to the conceptual foundation of systems of innovation was made by K. Smith[76],

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[66] R. Florida (2003), “Cities and the Creative Class”, *City & Community*, Vol.2, No.1, pp. 3-19 (p. 8).

[67] M.A. Weresa (2012), *Systemy innowacyjne we współczesnej gospodarce światowej*, Wydawnictwo Naukowe PWN, Warszawa, s. 14.

[68] C. Edquist (1997), Systems of innovation approaches: the emergence and characteristics, in: C. Edquist (ed.), Systems of Innovation: Technologies, Institutions and Organizations, Pinter, London, pp. 1-35.

[69] C. Freeman (1982), *The Economics of Industrial Innovation*, Pinter Publishers, London.

[70] B.Å. Lundvall (1992), National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning, Pinter Publishers, London.

[71] C. Freeman (1995), *The National System of Innovation in Historical Perspective*, “Cambridge Journal of Economics”, Vol.19, No.1, pp. 5–24.

[72] P. Cooke (2001), *Regional Innovation Systems, Clusters, and the Knowledge Economy*, “Industrial and Corporate Change”, Vol.10, No.4, pp. 945–974.

[73] F. Malerba (2004), *Sectoral systems of innovation: Concepts, issues and analyses of six major sectors in Europe*, Cambridge University Press, Cambridge, New York Melbourne.

[74] B. Carlsson, R. Stankiewicz (1991),“On the Nature, Function, and Composition of Technological systems”, *Journal of Evolutionary Economics*, Vol.1, No.2, pp. 93–118.

[75] T. Stahlecker, H. Kroll (2013), *Policies to Build Research Infrastructures in Europe – Following Traditions or Building New Momentum?*, Fraunhofer Institute for Systems and Innovation Research ISI Competence Center “Policy and Regions”, Working Papers Firms and Region No. R4/2013, Karlsruhe, p. 2.

[76] K. Smith (1997), Economic Infrastructures and Innovation Systems, in: C. Edquist (ed.), Systems of Innovation: Technologies, Institutions and Organizations, Pinter, London, pp. 86-106.

who explored the problem of defining infrastructures and their effects on the economic performance of innovation systems, with a focus on the role of public policy in developing and maintaining such infrastructures. In this study, infrastructures are defined as large-scale indivisible capital goods producing products and services, which become inputs in most or all economic activities on a multi-user basis. A special stress is put on knowledge infrastructures, such as universities, research laboratories, training systems, organizations related to standardization and the managing of intellectual property rights, publicly supported technical institutes, libraries and databases, etc. According to K. Smith, knowledge infrastructure performs several important roles in innovation systems, especially:

- production and diffusion of scientific and technological knowledge, enabled mainly by intense public R&D funding;
- production of skills, connected with the educational and training activities of R&D infrastructure institutions, in which there are the processes of personnel movement, with most of the entry into the institute sector coming from the university system, and most of the exit going to industry. This turnover process plays important but difficult to measure economic role as a process of technology transfer;
- establishing technical norms and standards, either implicitly by a specific research infrastructure, or through coordination of different stakeholders;
- creation of enterprises, as publicly supported infrastructures act very often as sources of new firms, which become the 'bearers' of new technology, translating it into economic results;
- access and dissemination functions, as a range of infrastructural organizations can be involved in maintenance of the existing stock of knowledge, in terms of storage, access, availability, dissemination, and so on.

In a sectoral perspective, research infrastructures play important role in development of some areas, for example emerging industries. M. Pero[77] understands research infrastructure as an entity, which provides access to cutting-edge scientific equipment and research services to the scientific community, thus promoting the exchange and diffusion of knowledge and know-how. In particular, he focuses on one of the research areas where research infrastructures are particularly important, namely materials sciences, characterized by a very wide application scope, ranging from metallurgy to nanotechnology.

Another important economic role of the knowledge infrastructures is that it can produce results that may be not only directly applicable to industrial production, but also used as inputs to the further production of knowledge. In this way, infrastructure-based R&D can open up opportunities that encourage enterprises to perform more R&D (additionality effect). As productivity growth is positively associated with R&D, the economic outcomes are therefore indirect but positive. To sum up, according to K. Smith knowledge infrastructure has been identified as a central component of the national innovation system[78].

3.3 Economics of network theory

The theory of economic network emphasizes the importance of external resource mobilisation, for example in research and innovation activity[79]. In a general understanding, network describes a

[77] M. Pero (2015), The position and role of research infrastructures in the materials science network, in: D.G. Assimakopoulos, I. Oshri, K. Pandza (eds), Managing Emerging Technologies for Socio-Economic Impact, Edward Elgar Publishing, pp. 186-214.

[78] K. Smith (1997), Economic Infrastructures and Innovation Systems, in: C. Edquist (ed.), Systems of Innovation: Technologies, Institutions and Organizations, Pinter, London, pp. 86-106.

[79] L.A. Oerlemans, M.T. Meeus, F.W. Boekema (1998), ”Do networks matter for innovation? The usefulness of the

collection of nodes and the links between them. However, there is some degree of network dynamics resulting from micro-decision of actors. It means that network structures can change because their members may develop strategies to create ties with other actors, based on their awareness of the network configuration. Nonetheless, examining the structure of any given network is a difficult task that requires to define and measure links or relationships[80].

Network approach enables understanding how social interactions impact economic outcomes[81]. In the context of research and innovation activity, networks contribute to the innovative capabilities of organisations exposing them to novel sources of ideas, enabling fast access to resources, and enhancing the transfer of knowledge. Formal collaborations may also allow a division of innovative labour that makes it possible to accomplish goals that single actor could not pursue alone. An important challenge to networks of innovation is developing capacity to simultaneously enhance the flow of information among current members and be open to new entrants[82]. An interesting contribution to this area is a network model of public goods[83] analysed on the example of innovation and information, which are often non-excludable in certain dimensions, so possess the public goods nature.

Network approach provides important insights into analyzing research infrastructures. The direction of the development of these type of organization is that they should not only as regionally or nationally available infrastructure, but should be rather taken into consideration as part of international research network. Research infrastructures can involve major network externalities, and they are often the place within a system where scale and scope economies are very significant. This implies that their existence or non-existence can significantly shape the fates of competing technologies, and thus the evolution of overall techno-economic systems[84].

The OECD case study[85] on CERN's network shows how institutional and personal contacts played a critical role in catalyzing R&D. In fact, CERN is one of the central nodes in a world-wide network of research-oriented organizations, which share and exchange knowledge, research tools and professionals. A well-developed network of links to national research agencies, institutions and laboratories in Europe and beyond brings a lot of numerous benefits. CERN employs some of the top experts in accelerator design, who apart from advanced knowledge, have an access to extensive international networks. The key point is that they have the capacity to develop long-range plans besides their primary work assignment. The presented case study indicates the open nature of the working environment of CERN as one of the reason of the richness and productivity of the network. Hence, openness, which is a prerequisite for networking, should get a prominent role in the functioning of European research infrastructures.

Another aspect of scientific and technological infrastructure is its potential participation in so called collective industrial research, which may be defined as "all establishments and activities designed to promote technical progress in a ranch of a particular industry sector or in a particular scientific or

economic network approach in analysing innovation", *Tijdschrift voor economische en sociale geografie*, Vol.89, No.3, pp. 298-309.

[80] M.O. Jackson (2008), Social and Economic Networks. Princeton, NJ: Princeton University Press.

[81] S. Goyal (2007), *Connections: an introduction to the economics of networks*, Princeton University Press, Princeton and Oxford.

[82] W.W. Powell, S. Grodal (2005), *Networks of innovators*, in: J. Fagerberg, D.C. Mowery, R.R. Nelson, *The Oxford handbook of innovation*, Oxford University Press, pp. 56-85.

[83] Y. Bramoullé, R. Kranton (2007), "Public goods in networks", *Journal of Economic Theory*, Vol.135, pp. 478-494.

[84] K. Smith (1997), Economic Infrastructures and Innovation Systems, in: C. Edquist (ed.), Systems of Innovation: Technologies, Institutions and Organizations, Pinter, London, pp. 86-106.

[85] OECD (2014), The Impacts of Large Research Infrastructures on Economic Innovation and on Society: Case Studies at CERN, The Organisation for Economic Co-operation and Development (OECD), Paris.

technical discipline which is being developed in industry"[86]. Collective research may be organised and finance in a variety of ways. The analysis[87] showed that this type of research network provides a unique framework for research on high-tech applications, by enabling collaboration across different sectors and technology fields. Therefore, collective industrial research proved to be successful in achieving the balancing act between the objectives of the network and in some cases diverging interests of the particular actors.

4. Monitoring and evaluating the economic impact of research infrastructures, with focus on potential indicators and available financial data

This part of the study reviews the methods and indicators that were indicated in the literature as suitable for the measurement of impacts of research infrastructures. Generally, it is difficult to identify and quantify impact in conventional commercial terms as this type of investment brings a broad range of social and economic benefits that are not captured by official statistics. In fact, there has been no unified framework for the impact assessment of research infrastructures developed so far. However, there are various conceptual frameworks, which aim to capture some direct or indirect impacts and longer-term effects of such investments.

One of the sources of potential indicators that may be used in assessing research infrastructures are publications of the European Commission. Key Figures report from 2008[88] used data on structural funds and expenditures on research infrastructures to determine the creation of new large-scale research infrastructures at the European level. The publication from 2013[89] states that indicators related to research infrastructures also include the most active research universities, funding models for universities (types of funding) and additional economic indicators, like the share of GOVERD in total public sector expenditure on R&D (GOVERD + HERD). Moreover, research infrastructures data may be used in the analyses of regional specialisation, as they enable to build critical mass in specialised domains of knowledge by establishing networks and partnerships, creating cooperative research organisations and supporting technology transfers. Sharing of specialised research infrastructures may enable regions to build strong clusters or cluster cooperation and facilitate cross-border knowledge sharing and research cooperation[90]. Therefore, there are important synergies between research infrastructures, regional specialisation, and clusters, which may be also exploited in statistical analyses.

Another theoretical methodology for evaluating the economic impact of research infrastructures is presented in Technopolis Group publication[91]. It distinguishes two main periods in the lifecycle of a research infrastructure, both of which require different methods and indicators when various direct and indirect benefits are monitored and evaluated:

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[86] R. Rothwell, W. Zegveld (1981), *Industrial Innovation and Public Policy*, Francis Pinter, London.

[87] M. Rothgang, B. Lageman, M. Peistrup (2011), "Industrial Collective Research Networks in Germany: Structure, Firm Involvement and Use of Results", *Industry and Innovation*, Vol.18, No.4, pp. 393-414.

[88] European Commission (2013), Directorate-General for Research and Innovation, *Cross-Cutting Analysis of Scientific Publications versus Other Science, Technology and Innovation Indicators*, Luxembourg: Publications Office of the European Union, p. 12-13.

[89] European Commission (2008), A more research-intensive and integrated European Research Area. Science, Technology and Competitiveness key figures report 2008/2009, Luxembourg: Office for Official Publications of the European Communities.

[90] Europe INNOVA/PRO INNO Europe (2008), The concept of clusters and cluster policies and their role for competitiveness and innovation: Main statistical results and lessons learned, Europe INNOVA/PRO INNO Europe paper N° 9. Commission Staff Working Document SEC (2008) 2637, p. 37.

[91] E. Griniece, A. Reid, J. Angelis (2015), Guide to Evaluating and Monitoring Socio-Economic Impact of Investment in Research Infrastructures, Technopolis Group, Tallinn.

1) design and construction phase;
2) operational phase of research infrastructure.

Focus on these two separate periods may be strongly relevant for the analysis of European research infrastructures, as many of them is still in the design and construction phase. Although they are still not operational, they may bring a lot of benefits: economic and for innovation. Economic advantages are mainly a result of all necessary physical investments in buildings etc. engaging many companies, which create job places and additional revenue in the economy. Innovation benefits are connected to a wide range of technical and scientific knowledge applied to set-up the required facilities. Requirements for different design solutions and building functionalities (e.g. laboratories) that are adjusted to the specificity of particular scientific discipline foster cooperation between scientific units, suppliers, and facility mangers, resulting in for example higher technology transfer. To conclude, the examples of indicators that measure economic and innovation indicators of research infrastructure in design and construction phase are presented in Table 2.

Table 2. Indicators of economic and innovation impact of research infrastructures in the construction phase

Area of impact	No	Indicators
Economic	1	Number of commercial suppliers for RI design and construction phase
	2	Scale of commercial suppliers' turnover increase due to RI
	3	Scale of commercial suppliers' employment increase due to RI
Innovation	4	Number of joint development activities with suppliers
	5	Number of contracts concluded for high-tech or specialist services that require development, or calibration of designs/equipment to meet specific requirements

Source: E. Griniece, A. Reid, J. Angelis (2015), *Guide to Evaluating and Monitoring Socio-Economic Impact of Investment in Research Infrastructures*, Technopolis Group, Tallinn, p. 6-7.

There is a much wider range of benefits that may be identified in the operational phase of research infrastructure. In general, the benefits may stem either from the routine operation, maintenance and upgrading of an infrastructure, or from the use of research facilities. There are five areas of impact of impacts of research infrastructures in the operational phase, as presented in Table 3.

Table 3. Indicators for impacts of research infrastructures in the operational phase

Area of impact	No	Indicators
Economic	1	Number of scientists, students, state-owned or private enterprises that benefited from RI services
	2	Total amount of funding generated from services, grants and joint projects
	3	Number of new directly and indirectly created jobs
	4	Total amount of expenditure on personnel, operations, maintenance
	5	Total RI capacity utilisation (measured by access hours used as % of the total available access time)
	6	RI capacity utilisation external business users
	7	Financial sustainability of RI (measured as % of the total costs funded from the provided services, received grants and realised joint projects
Innovation	8	Number of collaborative research projects and volume of funding
	9	Number of R&D projects commissioned by companies and volume of their funding
	10	Number of technologies, prototypes, industrial designs developed and transferred
	11	Number of start-ups and spin-offs created with support from RI services – growth in turnover/value added and employment
	12	Number of feasibility or market studies for industrial investment and application of technologies
	13	Procurement contracts signed for development and upgrade of research equipment
Human resource capacity	14	Number of new jobs for research and technical staff attracted from abroad as % of the total number of staff employed on RI
	15	Number of Master thesis defended, where knowledge and skills gained on RI were exploited
	16	Number of graduates trained on RI
	17	Number of foreign students as % of all students trained on RI
	18	Data on the post-diploma employment path of those graduates trained on RI
Scientific activity	19	Number of articles published in the ISI level international scientific journals as a direct result of research using RI
	20	Number of methodologies/designs developed
	21	International patents granted and published patent applications (all types)
	22	Number of PhD dissertations completed
	23	Number of scientific events organised on research topics directly relating to RI services
Society	24	Number of organised RI open days for wider public and any available data on participant satisfaction with the events
	25	Number of press articles on the investment in research infrastructure
	26	Number of new or improved products, services, solutions as a result of research using RI that are diffused in society
	27	Account of improved local infrastructure, community services, increase in local cultural/recreational activities due to RI

Source: E. Griniece, A. Reid, J. Angelis (2015), *Guide to Evaluating and Monitoring Socio-Economic Impact of Investment in Research Infrastructures*, Technopolis Group, Tallinn, p. 8-13.

Although there are different possible indicators that may be potentially used for evaluation an impact of research infrastructures, there are not relevant statistical data publicly available and they may be collected only through a direct research with regard to individual infrastructures, an implication is that the evaluation of the selected research infrastructures may be based on case studies, with application of some qualitative techniques, especially in-depth interviews with representatives of analysed research infrastructures. The case study research should lead to the collection of as many as possible information and data relating to indicators that are given in Tables 2 and 3 of this section.

Financial data on allocation of funds to the projects implemented by research infrastructures in the framework of FP7 and Horizon 2020 (part INFRA) for 2007-2015 period are used to calculate leverage effect, which shows how financing from the EU framework programs was assisted with spending from other sources, as presented in Table 4.

Table 4. Pooling the resources across Europe – common investments in research infrastructures

Years	Financing from EU part INFRA (EUR)	Project total budget (EUR)	„Leverage”
FP7 Ad Hoc 2007-2013	965 611.00	2 915 877.00	**3.02**
2007	290 374 607.86	9 338 170 347.94	**32.16**
2008	397 300 554.16	14 695 221 154.54	**36.99**
2009	9 599 808.00	261 246 688.00	**27.21**
2010	332 017 163.00	13 270 737 661.04	**39.97**
2011	258 446 268.92	8 334 309 891.04	**32.25**
2012	196 290 485.61	6 041 768 194.18	**30.78**
2013	44 300 000.00	5 685 830 659.00	**128.35**
Overall FP7 2007-2013	**1 528 328 887.55**	**57 627 284 595.74**	**37.71**
H2020 Ad Hoc 2014-2020	400 000.00	729 515.00	**1.82**
2014	230 450 300.50	5 558 223 553.03	**24.12**
2015	195 952 759.51	4 051 045 013.84	**20.67**
INFRAIA 2014-2015	160 601 006.38	4 208 666 195.10	**26.21**
Overall H2020 (until May 2016)	**587 404 066.39**	**13 818 664 276.97**	**23.52**

Own calculation based on data received from the National Contact Point for Research Programmes of the European Union, Poland.

The analysis of data from Table 4 shows that spending from EU framework programs was connected considerable amount of spending from other sources, in particular:

- 1 EUR spending from FP7 (part INFRA) involved on average 37.7 EUR total spending on co-financed projects,
- 1 EUR spending on RI from H2020 (until May 2016) was connected with 23.52 EUR of total spending on realized projects

The conducted analysis based on financial data on allocation of funds to projects implemented by research infrastructures in the framework of FP7 and Horizon 2020 (part INFRA) for 2007-2015 demonstrates that EU spending involved huge investments of funds from other sources, so they played positive role in pooling resources, which helps in reducing the negative impact of fragmentation of the European innovation system.

Conclusions

Conducted analysis of different definitions of research infrastructure shows that they underline mostly its material nature and physical component. However, a very important element of research infrastructures is also intangible sphere, as they are basically relational concept, constituting a part of a dynamic process of change, collaboration, and engagement. There are three most common types of research infrastructures are: 'single-sited', 'virtual' and 'distributed'. The most common research infrastructures are 'single-sited' The form of the research infrastructures depends strongly on the area of science, with stronger role of single-site laboratories in the field of energy and material sciences, distributed and co-operative facilities in environmental sciences, and virtual networks in the social sciences. In this study, roadmapping (understood as systematic strategic planning) was indicated as an important phase in the realization of large research infrastructures. This task has been made by the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap, which indicated the research infrastructures corresponding to the long term needs of the European research communities, covering different scientific areas.

The study demonstrates that main problems behind common EU investments in research infrastructures are: fragmentation of European innovation system (material or financial aspect), and lack of cooperation and interactions between research teams within and between different disciplines of science (intangible or interpersonal aspect). Corresponding two factors (pooling resources, and enhancing partnerships) are recognised as crucial for achieving critical mass needed to operate research infrastructures, taking into account their high complexity (technical, scale and costs) and increasing capital-intensity of modern research. The impact of the investments in priority European research infrastructures on overcoming identified two problems may be explained by different theoretical concepts. The first is the social capital theory, which suggests that the connections between external players lead to positive effects in raising resources (material component) and building interactions-enabling trust (intangible component). These factors stimulate knowledge creation and dissemination, as well as human capital development and employment, which are crucial for raising the innovativeness of the economy and its long-term competitiveness. Applying R. Florida concept, we may find research infrastructures as the creative centres, in which so called super-creative core of the creative class is deeply rooted and engaged in the problem finding and problem solving, subsequently resulting in the creation of innovation and economic growth. Next theoretical background comes from the concept of innovation system, in which knowledge infrastructure has been identified as a central component. This concept emphasises interdependences and interactions between the elements of the system, in which research infrastructures perform several important roles, mainly production and diffusion of knowledge and skills that affect the economy in two ways. First, they may be directly applicable to industrial production, influencing technological advancement of the enterprises and competitiveness, finally contributing to higher GDP. Secondly, they are used as inputs to the further production of knowledge, encouraging enterprises to perform more R&D (additionality effect), with indirect but positive implications for productivity growth. The last theoretical background applied is the concept of economic networks. It explains the need for pooling resources with regard to investments in research infrastructures as it emphasizes the importance of external resource mobilisation. Moreover, research infrastructures viewed as networks contribute to the innovative capabilities of organisations, by exposing them to novel sources of ideas, enabling fast access to resources, and enhancing the transfer of knowledge. This process results in major network externalities, and scale and scope economies, with implications for increased innovativeness and competitiveness of the European economy, and finally higher GDP.

The study reviews possible indicators that were indicated in the literature as suitable for the measurement of impacts of research infrastructures. The finding is that the set of possible measures differs for research infrastructures in design and construction phase and for these, which are in operational phase. The problem is there has been no unified framework for the impact assessment of research infrastructures developed so far. Although there are different examples of indicators that may be potentially used for analyzing an impact of research infrastructures, the relevant statistical data are not publically available. Most of data may be collected only through a direct research on the impact of the analyzed infrastructure (separately for each of them), which, if at all possible, would be very costly and time consuming process. An important source of knowledge to be used in case studies should come from, among others, in-depth interviews with representatives of research infrastructures, based on self-designed questionnaires. However, available financial statistical data on allocation of funds to the projects implemented by research infrastructures in the framework of FP7 and Horizon 2020 programs (part INFRA) demonstrate that these projects involved huge investments of funds from other sources, so they played positive role in pooling resources, which helps in reducing the negative impact of fragmentation of the European innovation system.

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