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Social benefits and costs of large scale research infrastructures

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ABSTRACT

This paper explores some of the methodological issues involved in a cost–benefit analysis framework for large scale capital-intensive research infrastructures. We propose a conceptual model based on the estimation of quantities and shadow prices of cost aggregates, and of six main categories of economic benefits: technological spillovers, human capital formation, knowledge outputs, cultural effects, services to third parties including consumers, and a public good, the pure value of discovery. We justify the reasons why these benefits of research infrastructures should be often expected to be the core ones in ex-ante project evaluation. Other benefits may be considered as well, but often by qualitative methods only. Empirical approaches are suggested for further applied research.

1. Introduction

Research, development and innovation are increasingly at the centre of political agendas as tools to stimulate economic growth, with the intellectual support of a new understanding by economists of the endogenous drivers of social change.[1] In the European Union (EU), the 'Europe 2020'[2] strategy includes the Innovation Union flagship initiative, aimed at transforming Europe into a world-class science performer, by establishing a common European Research Area and completing or launching the construction of priority European research infrastructures (RIs). Other countries, including China, are planning large-scale scientific ventures for the next decades.[3] In this paper we focus on the evaluation of large-scale research infrastructures. Governments are not always able or willing to foot the bill of Big Science.[4] In the early Nineties, the Superconducting Super Collider, an 87 km circumference particle accelerator, was to be built in Texas with an initial budget of USD 4.4 billion. After having already spent USD 2 billion and dug 23.5 km of underground tunnel and 17 pits, the cost for the project completion rapidly surged to USD 11 billion and the project was eventually abandoned by the US Congress (Baggott, 2012; Giudice, 2010; Maiani and Bassoli, 2012).

The increasing costs of RIs call for a critical evaluation of their social impact (Broad, 1990). Typically, the decision of funding highly expensive RIs is advocated by a coalition of scientists, often supported by peer reviews or other expert opinions, to convince the policy makers about the case for a new project. This process can be described as a lobbying approach to science policy. Lobbying is, historically, a feature of any major infrastructure decision process, e.g. in transport, energy, and water (see Cassis et al., 2015) and cost–benefit analysis (CBA) has evolved since its origins at the French École National des Ponts et Chaussées (Dupuit, 1844) as a way to counterbalance it. CBA consists in assessing whether benefits accrued from a project are in excess of its social costs, thereby showing if the project represents a net benefit to the whole society. The key strength of this approach is that it produces information of the project's net contribution to the society, summarized into simple indicators, such as the economic net present value (NPV).

Is it possible to adapt CBA methods in the context of Big Science? This is our research question.

Whatever the difficulty in estimating the social cost of any investment, because of lack of data or specific conceptual issues, particularly when externalities are considered,[5] a standard CBA theory for the estimation of their value to society is well established (see e.g. Drèze and Stern, 1987; Johansson, 1991; Johansson and Kriström, 2015; Pearce et al., 2006; Florio, 2014). There is a long worldwide experience in the CBA of traditional infrastructures, and more recently in environmental services, health, education and culture. This paper explores some of the methodological issues involved when evaluating RIs through the

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[1] See, for example, Griliches (1980); Adams (1990), Romer (1990), and Barro and Sala-i-Martin (2003).

[2] European Commission (2010).

[3] See for example the proposed Circular Electron Positron Collider (see cepc.ihep.ac.cn).

[4] The term 'Big Science' was coined fifty years ago to describe the large-scale character and complexity of modern science, in contrast with the formerly predominant 'Little Science' (de Solla Price, 1963; Weinberg, 1967).

[5] Projects aimed at tackling climate change are an extreme example. See the Stern Review (HM Treasury, 2006).

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CBA framework, and suggests that such a framework can be designed and applied empirically, with due caution given its experimental nature. However, in this paper we do not deal specifically with the issue of uncertainty, a crucial one for forecasting the social impact of RIs, because of the stochastic nature of many variables involved in the computation. This issue will be treated in a different paper (Florio et al., 2015b). In principle, all the variables included in the model that we are going to present should be considered at their expected value arising from an underlying probability distribution, according to the risk analysis framework (see Florio, 2014, Chapter 8). Thus we shall not repeat each time that in fact we are not dealing with a punctual forecast, but with a range of values for which the mean one is a convenient reference point under risk neutrality.

The structure of the paper is as follows: in Section 2, after defining the RI, we outline a conceptual CBA model and we propose and justify a taxonomy of benefits. Section 3 examines the social demand for RI and the social value of six main types of benefits. We discuss knowledge outputs, technological externalities, human capital development, wider cultural effects, services to third parties, and a non-use benefit: the pure value of discovery. For each of these six effects we mention empirical approaches for estimation of marginal social values. Section 4 concludes by putting together the cost and the benefit sides of the discussion, mentioning risk and the need for empirical research.

2. Conceptual framework

While CBA started in transport and water infrastructure, it then was applied in energy, telecommunications and other services. In the Eighties it was often maintained that investment in sectors such as education or health could not be evaluated by CBA techniques (see e.g. Baum and Tolbert, 1985), while this is now an accepted practice (see e.g. Viscusi and Aldy, 2003; the World Health Organization, 2006, on cultural projects in the UK see DCMS — Department for Culture, Media and Sport, 2010). Indeed there are some ingredients of RIs that are peculiar to them, but several are shared with other categories of infrastructures.

A *first* critical ingredient of any infrastructure is high capital intensity at an early stage of the project cycle (Gramlich, 1994). This is particularly true in Big Science, which is performed using some of the most expensive machines ever built. For the International Space Station, total costs are reported by the European Space Agency to be around USD 100 billion over a 30-year period.[6] Fixed investment costs of smaller RIs[7] also tend often to be larger that operating costs.[8] In contrast, we would exclude from the definition of RIs social surveys, since the service they provide is more labour, rather than capital, intensive, but see ESFRI — European Strategy Forum on Research Infrastructures (2011) which considers as RIs electronic surveys, such as the European Social Survey.[9]

A *second* ingredient is the long time horizon involved in both the cost side and the benefit side. For example CERN accelerators built in the late Fifties (Proton Synchrotron) and in the Seventies (Super Proton Synchrotron) are still used as injectors of proton beams in the Large Hadron Collider (LHC). The time horizon is however not necessary longer, and is often shorter than traditional infrastructures, such as e.g. roads, railways or dams. The time span of benefits is also long, as it is discussed below: decades if not centuries.

Third, 'standard' economic infrastructures are often associated with externalities and spillover effects: part of the economic benefits of an infrastructure is usually not appropriated by its owner, and we shall show that this is a core feature of RIs as well.

Fourth, there is no explicit market for all the services of the RI and very limited competition (Irvine and Martin, 1984). However, sometimes in Big Science the same research question could be answered in principle by more than one competing RI[10] (see Baggott, 2012). This adds to the interest of evaluating the relative costs and benefits of competing projects.

We argue that 'research' relates to all those activities which elaborate data and information for creating new knowledge. According to this criterion, RIs include both facilities for *pure* and *applied* research. University laboratories generally fall into this category.[11] Most of RIs are single-sited,[12] but there are also examples of geographically distributed facilities, such as grid computing systems or atmospheric measurement stations located in different areas and recording data which are then centrally studied.[13] In such cases there may be network externalities to be considered in the project's impact assessment.[14] Some RIs are mobile, as oceanographic vessels and satellites.

To sum up, for the purpose of the CBA conceptual framework suggested in this paper we understand RIs as (a) high-capital intensity, (b) long-lasting facilities or networks (c) typically operating in 'monopoly' or 'oligopoly' conditions, and affected by externalities (d) whose objective is to produce social benefits through the generation of new knowledge, either pure or applied.

The literature on the social benefits stemming from research is huge, and in some earlier RI literature[15] many 'positive outcomes' are listed. We are not going, however, to review here such literature on the social impact of technology progress, innovation and science, a stream that has been blooming over decades, with a variety of approaches, going from adaptation of macroeconomic tools, such as aggregate production functions augmented with R&D expenditures and input–output models, micro-econometrics applied to firm-level data, patent data, business surveys, and qualitative approaches. For recent surveys or critical reviews see for example OECD (2014b), Martin and Tang (2007), Technopolis (2011), European Space Agency (2012), Browny and Rosenberg (2010) and the reviews by Del Bo (2014) and Gomez (2015). While we take advantage of the deeper understanding of the social impact of research and experimental development thanks to earlier literature, and some of it will be cited later in the discussion of specific social benefits of RIs, we focus here exclusively on its relevance for a CBA framework.

We propose to consider a simple CBA model for RIs consistent with applied welfare economics principles (Florio, 2014). Before introducing the model we discuss qualitatively the identification of beneficiaries of research infrastructures, as ultimately a CBA aims at tracing the social impact of a change on individual economic agents or their aggregates. Then, in the rest of the paper, we discuss each of the model components.

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[6] http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/How_much_does_it_cost.

[7] Examples include the Italian Laboratory for the Study of the Effects of the Radiation on Material for Space, the Finnish Centre of Excellence in Environmental Health Risk Analysis or the Hungarian Cyclotron of Atomki that provides accelerated particles that can be used for nuclear physics studies and for radioactive isotope production for application purposes.

[8] http://www.riportal.eu/public/index.cfm?fuseaction=ri.search.

[9] The European Social Survey is a network established to develop, store and study long time series of data used to monitor and interpret changes in European social attitudes and behaviour patterns.

[10] A comparative assessment of the advantages and disadvantages of the CERN Large Electron-Positron (LEP) collider was conducted by Irvine and Martin (1984). This exercise shows that even very large and cutting-edge accelerators might have a number of rival projects.

[11] However, some university departments are not to be considered RI, but rather education facilities.

[12] Examples of single sited RIs include particle colliders, telescopes, research vessels and aircrafts, science parks, laser light facilities, microscopy facilities, research nuclear reactors, laboratories for zoology, botany, and some supercomputers.

[13] Other examples are seismographic stations and aquaculture and laboratory testing facilities.

[14] According to OECD (2014a) a distributed infrastructure is a network or multi-national association of geographically-separated organisational entities that jointly operate a set of independent research facilities, e.g. the European Very Large Baseline Interferometry Network that is a collaboration of the major radio astronomical institutes of Europe, Asia and Africa.

[15] See Salter and Martin (2000); Hallonsten et al. (2004); SQW Consulting (2008); Czech Ministry of Education, Youth and Sport and JASPERS (2009); Science and Technology Facilities Council (2010); COST Office (2010); JASPERS (2013); and Bach (2013).

A customary partition of economic agents in the applied welfare economics literature, particularly in a general equilibrium perspective (Drèze and Stern, 1990, Florio, 2014, Johansson and Kriström, 2015) is as follows: firms, consumers, employees, and tax-payers. Firms are ultimately owned by individual share-holders, and have an objective of profit maximization (in a partial equilibrium frame this is equivalent to producer surplus); consumers want to maximize their utility (represented by consumer surplus when looking at a specific market); employees want to maximize their income for a given amount of effort; and tax-payers adjust their decisions as a consequence of the existing fiscal constraints to minimize the burden of taxation. Obviously most tax-payers are also employees, some of them are share-holders, all are consumers, and there are other combinations of roles and possible disaggregation of these simplified social categories. Thus, it is natural to look at research infrastructures as projects, i.e. changes of the world, affecting each type of agents in different ways.

On the cost side, firms under procurement contracts with a RI project earn profits; scientists and other staff, including Ph.D. students and trainees deliver effort; consumers may be affected by negative externalities, such as environmental impact of construction work, and taxpayers foot the final bill if the RI needs funding by the government. On the benefit side, firms under procurement benefit from learning by doing effects because of new challenges and interactions with advanced researchers, and will earn future profits from patents and sales in other markets; other firms will enjoy cost savings because of innovations, particularly when such innovations are an externality, i.e. are appropriated for free; the utility of consumers may be directly affected by services provided to them by the RI (for example services of medical research facilities, new environmental monitoring, or cultural services related to outreach) or indirectly as part of the innovation will translate in technological progress, cost savings, and relative price decrease of goods; taxpayers, against the burden of paying for the government funding of a RI, benefit of potential (albeit often highly uncertain) future benefits (a quasi-option value) and a the utility arising from pure knowledge per se, a public good having an existence value. We shall discuss each of these effects in detail in Section 3.

A CBA model for RIs should then try to capture as far as possible these effects on economic agents, who ultimately are the fabric of the society, and ask the question whether the positive welfare effects are greater than social costs. This question is clearly different from the scientific or technological case for a RI project, financial sustainability, its relevance for national policies (including defence or security), managerial issues, and several other topics frequently dealt with in the economics of innovation literature. These issues are interesting per se, but in a different perspective. We turn now to the main ingredients of a CBA model for RIs.

We define the forecast of the economic NPV of RI over the time horizon $\mathcal{T}$ as the expected intertemporal difference between benefits and costs valued at shadow prices, which in turn are defined as the marginal social value of goods, i.e. the change of welfare because of the small change of supply of one good. We assume as given the time horizon[16] of the analysis and the social discount rate, used to translate future values into present ones.[17] We suggest that for RIs, that NPV can be decomposed into two parts: the net present value of use-benefits and costs (NPV_u) and the non-use value of discovery (B_n).

$$NPV_{RI} = NPV_u + B_n = \left(PV_{B_u} - PV_{C_u}\right) + B_n. \tag{1}$$

The present value of use-benefits PV_{B_u} is the sum of

- benefits to firms, that we define as technological externalities (T);
- benefits to staff, particularly students, arising from human capital accumulation (H);
- benefits to users of the RI services including the value of publications for scientists (S);
- cultural effects (C);
- benefits of applied research to external users or other consumers (A).

Non-use benefits (B_n) refer to the future possible effects of any discovery that the RI might find (quasi-option value) and the pure value of discovery per se, a public good. The present value of costs PV_{C_u} is the sum of the economic value of capital (K), labour cost of scientists (L_s) and other administrative and technical staff (L_o), other operating costs (O) and negative externalities if any (E):

$$NPV_{RI} = [T + H + S + C + A] + B_n - [K + L_s + L_o + O + E]. \tag{2}$$

The discounting process, here and below, is represented by the $\mathcal{T}$ terms: $s_t = 1/(1+r)^t$. Starting with effects on firms and professional activities in general, the present value of technological spillovers T is given by the discounted incremental social profits Π_{jt} by companies (j) of the RI's supply chain or other economic agents, who have benefitted from a learning externality:

$$T = \sum_{j=1}^{J} \sum_{t=0}^{\mathcal{T}} s_t \cdot \Pi_{jt}. \tag{3}$$

Human capital accumulation H is valued as the increased earnings (I) gained by former RI's students and former employees (z), since the time (φ) they leave the RI project, against a suitable counterfactual scenario:

$$H = \sum_{z=1}^{Z} \sum_{t=\varphi}^{\mathcal{T}} s_t \cdot I_{zt}. \tag{4}$$

Scientists are not only producers but also 'consumers' of knowledge outputs generated by the RI. The direct value of such knowledge output S (i.e. of the output per se, mainly publications and preprints, not of the wider effects of its content) is measured by a chain effect in the literature. An operational shortcut to estimate the social value of knowledge consists in computing the sum of the present value of papers authored by RI's scientists (P_{0t}), the value of subsequent flows of papers produced by other scientists using the results of RI's scientists, divided by the number of references they contain ($\frac{P_{it}}{k_{it}}$, with $i = 1, \ldots n$) as a proxy of the RI literature input, and eventually the value of citations each paper receives, as a proxy of the social recognition that the scientific community acknowledges to the paper (Q_{it} with $i = 0, \ldots n$):

$$S = \sum_{i=1}^{n} \sum_{t=0}^{\mathcal{T}} s_t \cdot P_{0t} + \sum_{i=1}^{n} \sum_{t=1}^{\mathcal{T}} \frac{s_t \cdot P_{it}}{k_{it}} + \sum_{i=0}^{n} \sum_{t=1}^{\mathcal{T}} s_t \cdot Q_{it}. \tag{5}$$

Taking a service marginal cost as an empirical proxy of its social value is a standard practice in CBA when the marginal willingness to pay for such services is not available, an idea accepted since the Little and Mirrlees (1974) methodology developed the distinction between traded and non-traded goods. As the market value of scientific publications and the willingness to pay by scientists for being published, being read, and being cited are not available, taking the marginal cost is

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[16] It seems reasonable to assume a long, but finite, time horizon for the benefits of a RI, given the obsolescence process of the value of knowledge over time, which is observable, for example, in the time trend of citations of the RI related literature or patents. The residual value of these effects can be included in the final year of the analysis.

[17] The social discount rate (SDR) expresses the rate at which society is willing to postpone a unit of current consumption in exchange of more future consumption. In most of CBA practice, a constant discount rate is used, which implies an exponential discounting process of the project's inflows and outflows. For the very distant future a low discount rate is adopted by the Stern Review on the Economics of Climate Change (HM Treasury, 2006). Declining SDR has also been proposed (HM Treasury, 2003).

justified, and probably conservative. To clarify this intuition, it is worth remembering that the output of public services in the System of National Accounts (SNA, 2008) is based on their cost, hence a large part of the valuation of GDP (for example provision of public health and education, law and order, or environmental protection is based on production cost accounting).[18]

Outreach activities C carried out by the RI produce different cultural effects on the general public (g), which can be valued by estimating the willingness to pay W_{gt} for such activities:

$$C = \sum_{g=1}^{G} \sum_{t=1}^{\mathcal{T}} s_t \cdot W_{gt}. \tag{6}$$

The present value of benefits produced by (mainly applied) research infrastructures on other users and the economic value of services provided by the RI (A) is:

$$A = \sum_{a=1}^{A} \sum_{t=0}^{\mathcal{T}} s_t \cdot a_t. \tag{7}$$

These services are project specific (health for example), and each of them ultimately is related to the WTP for them by users. Finally, the term B_n captures two types of values related to the research discoveries: their quasi-option value (QOV_0) and the pure or ‘existence’ value (EXV_0) evaluated at present time:

$$B_n = \mathrm{QOV}_0 + \mathrm{EXV}_0. \tag{8}$$

When QOV_0 is in general intrinsically uncertain and therefore not measurable, it is simply assumed to be non-negative and can then be skipped (see also Pearce et al., 2006, who suggest not to include QOV but to consider it separately). EXV_0 on the other hand, is the social value of a pure public good and can be proxied by stated or revealed willingness to pay for discovery (and/or through a benefit transfer approach from similar projects). These concepts are not new, but their application to RIs evaluation is novel, and we shall discuss in detail them later on.

Turning to RI costs, their present value can be expressed as:

$$PV_{C_u} = \sum_{t=0}^{T} s_t \cdot (k_t + l_{st} + l_{ot} + o_t + \varepsilon_t), \tag{9}$$

where k_t is the annual capital cost, l_{st} and l_{ot} are the scientific labour and administrative/technical labour respectively, o_t is the other operating cost and ε_t is the value of negative externalities. If the marginal cost of scientists' labour input in publications is taken as a proxy of the value of knowledge outputs produced by scientists, then l_{st} in Eq. (9) and P_{0t} in Eq. (5) cancel each other (under the reasonable assumption of linearity of the cost function).

Summing up: the CBA model for pure and applied research infrastructures turns into the following equation:

$$\begin{aligned} NPV_{RI} = {} & \left[\left(\sum_{j=1}^{J} \sum_{t=0}^{\mathcal{T}} s_t \cdot \Pi_{jt} \right) + \left(\sum_{z=1}^{Z} \sum_{t=\varphi}^{\mathcal{T}} s_t \cdot I_{zt} \right) + \left(\sum_{i=1}^{n} \sum_{t=1}^{\mathcal{T}} \frac{s_t \cdot P_{it}}{k_{it}} + \sum_{i=0}^{n} \sum_{t=1}^{\mathcal{T}} s_t \cdot Q_{it} \right) \right. \\ & \left. + \left(\sum_{g=1}^{G} \sum_{t=1}^{\mathcal{T}} s_t \cdot W_{gt} \right) + \left(\sum_{a=1}^{A} \sum_{t=0}^{\mathcal{T}} s_t \cdot a_t \right) \right] + (\mathrm{EXV}_0) \\ & - \left[\sum_{t=0}^{\mathcal{T}} s_t \cdot (k_t + l_{ot} + o_t + \varepsilon_t) \right]. \end{aligned} \tag{10}$$

The CBA test could produce three possible baseline results (i.e. without considering explicitly their probability distributions):

- The net present use-value of the research infrastructure NPV_u (all the terms except the last one) is greater than zero, i.e. $PV_{B_u} > PV_{C_u}$ hence $NPV_u > 0$;
- The net present use-value of the research infrastructure is equal to zero net of the non-use effects, $NPV_u = 0$;
- The net present use-value of the research infrastructure is negative net of the non-use effects, $NPV_u < 0$.

In the first two cases the RI passes the ex-ante CBA test if the evaluator *guesses* that the uncertain B_n would be at least nil, so that the total NPV_{RI} cannot be expected negative (within a range of associated probabilities). In other words, when the use-benefits of the RI are at least equal to the costs of producing them, in principle there is no further need to try to estimate B_n, as long as it can be excluded that non-use effects are non-negative. This is clearly a considerable computational advantage. The pure public good of discovery, if any, is still an externality of the project, but the society gains or at least does not lose by having the RI. We suggest that for many RIs in applied research and technological development the CBA test should be passed on these grounds. If not, the case for funding the project with government funds is more difficult, and cannot be supported by CBA, and should be justified in some other way (if it can be justified).

In the third case, which may be typical of fundamental research, the RI project passes the CBA test if and only if B_n is positive and large enough to compensate for the negative net use-effects. In this situation, we can no more avoid an estimation of the willingness to pay for the pure value of discovery as a public good. As mentioned, what is needed here is a *guess*, a conjecture of the possible impact of the discovery on social welfare. We discuss the nature of such guess below in Section 3.6 and we claim that empirical measurement of the social value of EXV_0 in principle is possible, albeit with due caution, while in general we suggest to set to zero the QOV_0 component (even if one may think that in special cases there is some information on it).

Once having defined the taxonomy of benefits of RIs, for each benefit there are two crucial steps to take in order to implement a social CBA. The first is forecasting the benefit in quantitative terms. The second step is valuing it through a shadow price, which expresses the social value of a marginal change in the availability of the good (MSV).

The estimation of shadow prices is the main conceptual difficulty involved with the calculation of the NPV. Drèze and Stern (1987, 1990) prove that, in some cases, the shadow price of a good can coincide with its long run marginal production cost (MPC), i.e. the social cost of increasing the production of that good by one additional unit, holding the production level of all other goods constant. An alternative approach to shadow price estimation is to consider the willingness to pay (WTP) stated by the project users or indirectly revealed through specific techniques. This approach is particularly appropriate to determine a monetary value for non-market goods. In some circumstance, the MSV of a good can also be obtained by a combination of the long run MPC and WTP.[19]

The rationale for using shadow prices in place of observed market prices when evaluating the welfare impact of infrastructure projects relies on the fact that shadow prices better reflect the MSV of goods in an economy where markets are not perfectly competitive and efficient and market prices are likely to be distorted. The main reason why market prices are unlikely to represent a relevant signal for the decision makers of research infrastructure projects, is because the most relevant goods produced by the RI are either public goods, like non-excludable and non-rival knowledge, whose market prices typically do not reflect the opportunity cost of the good, or externalities, like technological learning, for which prices do not even exist. In general, this peculiar exchange of capital, labour, consumption and non-market goods, that we shall discuss below, is such that the price system does not work efficiently, and this is our case for using social CBA at shadow prices in this context.

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[18] http://unstats.un.org/unsd/nationalaccount/sna2008.asp.

[19] Florio (2014) discusses in detail the empirical issues involved.

In the next section we turn to a more analytical discussion of quantification and valuation issues regarding each of the abovementioned RI benefits, starting by the use-benefits and turning then to the non-use value of discovery.

3. Evaluating the social benefits

We start our discussion with the effects of RIs on firms, we turn then to human capital formation, then to different types of benefits to users or consumers and eventually we discuss the non-use benefits. While we shall give some examples of empirical issues and results, a more detailed discussion is in Florio et al. (2015b), and in the two case studies of the CBA of the Large Hadron Collider — LHC (Florio et al., 2015a) and of the Italian Centre of Hadrontherapy — CNAO (Pancotti et al., 2015).

3.1. Technological externalities

Building a new large and complex infrastructure or carrying out an experiment at the scientific and technological frontier can be an important source of innovation (Lederman, 1984; Kay and Llewellyn Smith, 1985; Mansfield, 1991; Technopolis Group, 2013; Del Bo, 2014). A well-known example of technological spillover is the invention of the World Wide Web at CERN in 1989, initially conceived as a means to improve the sharing of information between scientists working on CERN experiments. The LHC computing grid project allows a volume of information that currently exceeds the capacity of any computing facilities in a single site to be linked, distributed and analysed (Boisot et al., 2011). Grid computing is widely used in climatology, astronomy, biology and others (Giudice, 2010: 138) and has attracted the attention of the core players in the computing industry. The Global Positioning System (GPS) was originally intended by the US Department of Defense for military applications before being made available for civilian use in the Eighties[20]; and a wide range of new materials and tools stem from space technologies needed for the NASA projects, such as the ‘memory foam’ able to deform and absorb pressure and to return to its original shape: invented to improve the safety of aircraft cushions, it is nowadays used for helmets, mattresses or wheelchair seats.[21] Other widespread innovations originated at the European Space Agency, the European Southern Observatory, European Synchrotron Radiation Facility, European Molecular Biology Laboratory, etc. Technological spillovers might occur also within the firms and laboratories along the RI's supply chain. When a procurement contract for the RI is signed, an intense collaboration process between the suppliers and the RI staff gets started aimed at effectively designing, testing and manufacturing the required product or service. These efforts give firms the opportunity of learning something new.

The analytical issue involved in estimating the technological impact of RIs is two facets, as mentioned in Section 2: i) how to identify and measure spillovers and ii) how to value it. If the research and development cost is fully internalized by the firm, and is then repaid by the procurement contract, there is no identifiable ‘first round’ externality. However, this does not bar ‘second round’ effects from occurring. Innovation spilling over the scope of the initial procurement contract can be, at least to some extent, attributed to the knowledge acquired on the job.[22] Learning-by-doing as an externality of R&D activities has received great attention in the economic literature on endogenous growth. In the Arrow model (Arrow, 1962) the rate of growth of technology depends on the rate of growth of capital, reflecting the fact that productivity increases in parallel with production. Higher productivity and, hence technological change, are expected to lead to higher profits. Of course, the absorptive capacity of the firm, this being its ability to recognise the value of new information or skill and to assimilate it and apply it to increase its profits, is a critical factor (Cohen and Levinthal, 1990).

There exists a vast literature analysing the relationship between academic research and industrial innovation activity. For example, an econometric analysis by Jaffe (1989) found a significant positive impact of the university R&D on industrial patenting in 29 US states, see also Bacchiocchi and Montobbio (2009). On the same line of thinking, Cowan and Zinovyeva (2013) have recently analysed the effects produced by the opening of new universities in Italy during 1985 and 2000 on regional innovation, in terms of the number of patents filed by firms, and confirmed the existence of a positive relation. Other studies show that university research also positively affects firms' product and process innovation (Acs et al., 1992; Feldman and Florida, 1994).

The empirical literature focusing specifically on the technological spillovers of RIs is less developed. The first studies were drafted in the Seventies by the NASA in the US and CERN in Europe. These studies usually rely on a qualitative methodology of analysis and case studies, developed through desk research, in-depth interviews and surveys. Autio et al. (2003) investigated the learning benefits gained by European firms that had participated in CERN's procurement activity between 1997 and 2001. A sample of firms was selected from the total number of suppliers to CERN during the considered period (6806 firms), excluding those companies whose total order did not exceed CHF 25,000 and which provided only off-the-shelf products or very simple services.[23] The sampling process led to 612 companies that supplied a noticeable technological development or innovation components.[24] A survey was then submitted to this sample of firms and based on the answers provided by the respondent firms (154), the authors found that the benefits associated with procurement activity can be in terms of significant technological and market learning (respectively 44% and 36% of firms), increased international exposure (43%), new products developed (38%), new markets opened (17%), new business units established (14%) and new R&D units started (13%). Respondents also declared that, without CERN, they would have had less sale and technological performance (52% and 41%), lower performance in valuation growth (26%), and lower employment growth (21%). More recent data refer to the ATLAS experiment, see Autio et al. (2011), and Boisot and Liyanage (2011). An additional innovation outcome that might be produced by RIs is the creation of spinoffs, aimed at commercialising the facility's research breakthroughs. NASA has been tracking its spinoffs since 1976 and has now a database including 1800 spinoff case studies,[25] the majority of which associated with the Langley Research Centre, the Johnson Space Centre and the Marshall Space Flight Centre. In general, an average of 48 spinoffs are generated every year by NASA research infrastructures.

From an ex-ante point of view, one way to forecast the possible size of technological spillovers of the RI under assessment is to take already existing similar RIs as a benchmark and rely, as far as possible, on the opinion and expectations of experts about the similarity or dissimilarity of technological patterns. As mentioned in Section 1, the probability of error can be tested through a fully-fledged risk assessment. Ideally, one should look at the social profits generated by the spillovers, catered from the company's return on sales (corrected with shadow prices of inputs and outputs as needed). Being j the number of companies benefitting from technological spillovers over time $\mathcal{T}$, Π_{jt} their incremental

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[20] http://geography.about.com/od/geographictechnology/a/gps.htm.

[21] http://science.howstuffworks.com/innovation/inventions/top-5-nasa-inventions.htm#page=1.

[22] In this vein, Giudice (2010: 109) reported that: ‘Many of the companies that worked for the LHC project are now using the new skills learned in the process. For instance, one company is producing superconducting material for medical magnetic resonance imaging and another has applied a special production process started for the LHC to manufacturing automobile parts’. See also the UK Science and Technology Facilities Council (2010) on other examples (e.g. the Darensbury Synchrotron Radiation Source).

[23] Like catering or training.

[24] They represent less than 10% of the total number of suppliers to CERN, but 56% of CERN's total procurements during the period (CHF 1197 million). Their fields of activity spanned from information technologies, to magnets, cryogenics and vacuum technologies.

[25] NASA online spinoff database, available at http://spinoff.nasa.gov/spinoff/database.

shadow profits (i.e. profits at shadow prices) directly imputable to the spillover effect, and given the discount factor, the present value of technological externalities is expressed as:

$$T=\sum_{j=1}^{J}\sum_{t=0}^{T}\frac{1}{(1+r)^{t}}\cdot \Pi_{\mathrm{jt}}=\sum_{j=1}^{J}\sum_{t=0}^{T}\frac{1}{(1+r)^{t}}\cdot \\ =(\Delta \mathrm{revenues}_{\mathrm{jt}}-\Delta \mathrm{costs}_{\mathrm{jt}}) \qquad (12)$$

where the last term is the difference between incremental revenues and costs. If innovation decreases costs, profits increase. The average firms' return on sale (ROS, possibly using income gross of taxes, interest and depreciation to be closer to a cash-flow frame) reported in balance sheets can be taken as a proxy of social profit in competitive markets; in distorted markets, so that observed prices do not reflect the real opportunity cost of resources, the profit has to be derived as the difference between the firms' total income or cash inflow and operating costs, all valued at shadow prices (see Section 2).

Our approach is broadly in line with the empirical literature, where R&D spillovers and externalities are captured through variations in the private profit margins (e.g. Hall et al., 1999; Hall et al., 2009 and Mansfield et al., 1977), and it can be adopted also in a CBA framework subject to the important proviso that only variations in profits that are ascribable to the activities carried out by RI's supplier are considered. This is easy in the case of new spin-off companies created to commercialise a technology associated with the RI, whose benefit is reflected in the cumulative profit made by the company during its entire lifecycle.

The increase of profit in principle should be assessed against a counterfactual group of companies, operating in the same sector and sharing other characteristics with the companies that actually worked for the RI, in order to control for selection bias. The set of techniques typically used for implementing a counterfactual impact evaluation,[26] which are well established especially in the evaluation of the effects of government subsidies on private R&D in the European Union,[27] can be relevant also in the RI context. While ex-post a survey to companies within and outside the supply chain of the RI could be set up, one crude form to value the technological progress ex-ante would be to use a 'benefit transfer' approach, i.e. giving a money value to innovation indicators related to a specific project plugging in a value estimated from existing knowledge elsewhere. This is imprecise, but better than using only subjective guesses. For example, if a range of estimates about the marginal impact generated from R&D activities on firm profitability due to its direct exposure to the RI is available, we may transfer this information to the RI project under assessment and use it as a proxy for the technological externalities on the supply chain.

The idea of tracking patents linked to the development of RI projects,[28] as suggested in some literature (see among others Scherer, 1965; Schmookler, 1966; and Hall et al., 1986), could provide a useful but only partial indication of the total innovation produced. As a matter of fact, not all innovation generated both by the RI owner, its scientists and technical staff, and by firms in its supply chain is patentable or might be actually protected by a patent.[29] In general, the increase of profits ascribable to the RI against a realistic counterfactual should provide a most comprehensive measure of technological spillovers, accounting for the benefits related to the production of a new marketable product, the commercial exploitation of a patent, the increase of productivity, and also increase of visibility and corporate's image (SQW Consulting, 2008: 31).

The approach here suggested to value technological externalities cannot be confused with the way sales or increased efficiency and performance are generated by procurement contracts. Some studies define the economic benefit of technology transfer as the sum of the increase of turnover and saving in production cost generated by, but independent from, the procurement contracts. In the context of CERN, for example, Schmied (1975) and Bianchi-Streit et al. (1984) analysed the supply chain of CERN respectively in the periods 1955–1978 and 1973–1982. The former study, based on data collected through interviews to a sample of 134 European firms (127 respondents) suggests that the 'economic utility' ratio was in the range 1.4 and 4.2 with an average of 3. This figure would indicate that for every Euro spent by CERN in a high-tech contract, a company receives around 3 Euros in the form of increased turnover or cost savings. As stated by Schopper (2009: 150):

> 'this implies very crudely that in a laboratory such as CERN about one quarter of the budget is spent on high-tech products and consequently around three quarters of the overall public spending is eventually returned to industry'.

Improving the sampling and extrapolation methods, Bianchi-Streit et al. (1984) obtained the same average utility/sales ratio. Other studies (mentioned by Autio et al., 2011) report ratios of total value added to contract value of 2.7 in the case of the European Space Agency, and between 1.2 and 1.6 for Big Science centres (see also Florio et al., 2015b).

However, these calculations seem to implicitly assume that the value of the externality can be computed simply as increased sales and decreased costs. In general, however, we maintain that it is not the change of sales that needs to be considered, but the change of *net* output (i.e. profit) at shadow prices. If shadow prices are simply estimated equal to market prices, this would be the net present value of the additional gross profit.

Since we argue that the value of technology depends on its economic utility, innovation that remains commercially unexploited and does not currently produce an actual increase of profits cannot be valued as a technological use-benefit of the project. It is part of the quasi-option value, see below.

3.2. Human capital formation

A large-scale research infrastructure attracts Ph.D. students and junior scientists, often from abroad. Their motivation lies in the willingness to be 'part of the show, to be a player associated with one of the world's biggest scientific experiments' (Boisot and Bressan, 2011: 206). Many skills acquired at the RI could find practical application in careers outside scientific research. Schopper (2009) states that around 40% of students working at CERN eventually go to industry, even 60% according to Maiani and Bassoli (2012). Camporesi (2001) analysed the careers of more than 600 diploma, masters and Ph.D. students involved in one of the Delphi experiments at the LEP accelerator between 1982 and 1999. While 57% of them continued doing research and teaching in the academic context, 43% found their first occupation in the private sector, especially in the field of high technology and computing. Catalano et al. (2015) provide an update for LHC related experiments and subsequent careers.

In contributing to the training of young scientists worldwide, in fact most RI projects are similar to research universities, with one main difference: usually students do not pay a fee for their on-the-job training, but the opposite may be true, as students are often supported by a fellowship. There seems to be a clear externality here, and the shadow price is, as usual, the MSV of such on-the-job training. In this perspective, insights from the economics of education can be utilized to gauge

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[26] Difference-in-difference, discontinuity design, matching approach, etc.

[27] See for example Gadd et al. (2009); Mouqué (2012) and ASVAPP (2012).

[28] Either through names of inventors associated with patents, or of firms, or keywords.

[29] The OECD study 'Turning science into business' (2003) shows how skewed the distribution of licensing revenue per license is: 'While some [Public Research Organisations] in the United States generate several million USD from licenses, the average value of each license in 2000 was USD 150,000' (OECD, 2003: 16). In Switzerland the average revenue per license is much lower, EUR 45,000. The EIB (2013) reports an average yearly revenue per licence in Germany of EUR 55,000, with a higher average (EUR 200,000) for licenses of the Max Planck Institute. This issue is also discussed by the new EC Guide to CBA (European Commission, 2014).

the contribution of RIs to the increase of human capital available to society. Both theoretical and empirical analysis[30] suggests that secondary and higher education and training positively contribute toward economic growth by increasing the productivity of the labour force. A quasi-experiment perspective would be needed to assess the effect produced by the RI on young scientists. In its more appropriate form, this would imply tracking careers of cohorts of students in the long run and matching data on careers of scientists involved in RI projects with those who have not been involved. However, in many situations controlled experiments are not a feasible solution because data on careers for RI students and of a suitable control group are not easily available. Ex-ante these data are not available.

In the absence of quasi-experimental evidence, the standard approach would be to set up an econometric model so as to estimate the marginal effect of human capital formation on the earnings gained in the entire lifetime. Mincer (1974) human capital earning function disaggregates individual earnings, into a function of an education term (as given for example by the number of years of education, or the degree) and experience (as measured by the number of years of work since completion of schooling), a constant parameter and an error term. Instrumental variables (IV) are usually used to reduce the correlation between the explanatory independent variables and the error term. Instrumental variables could relate to the student's country of origin, gender, race, parents' level of education, quality of the education, and so on.[31] A review of the literature carried out by Card (1999) shows that IV estimates of the return to education are in the range of 2.4%–11%. A European survey by Psacharopoulos (2009) reports a minimum private return to higher education[32] of 2.1% in Croatia to more than 20% in Czech Republic, Poland and Portugal (2004 data), with an average of 10.2% in 31 European countries.[33] It also finds that there is a weak inverse relationship between the returns and the country's per capita income. The evidence for the return to different higher education facilities is more limited. A study on UK faculties (O'Leary and Sloane, 2005) indicates high returns associated with maths and computing (21.1%), education (19.4%), medical related (17.4%) and engineering (15.8%) degrees; returns associated with education in sciences, business and economics and social sciences are around 12%; the lowest return is associated with arts (4.1%). It is worth to note that the lesser RI-specific skills acquired by students and technical staff are, the larger the human capital formation benefit could be (Boisot and Bressan, 2011).

The present value of human capital accumulation benefits produced by the research infrastructure project can then be defined as the sum of the increasing earnings or income, *I*, gained by RI's students and former employees, commonly indexed by *z*, since the moment (at time φ) they leave the project.

$$H = \sum_{z=1}^{Z} \sum_{t=\varphi}^{\mathcal{T}} s_t \cdot I_{zt} = \sum_{z=1}^{Z} \sum_{t=\varphi}^{\mathcal{T}} \frac{1}{(1+r)^t} \left(I_{IRzt} - I_{CFzt}\right) \tag{13}$$

where the last term is the difference between the income after the training at the IR and a counterfactual income.

Preliminary testing of our approach with the LHC case study (Florio et al., 2015a) shows that the size of *H*-benefit can be substantial compared to other ingredients of Eq. (2), mainly because of the high number of students and junior researchers attracted in a large RI, and above all because of the long duration of the effect.

We consider now the welfare on different categories of users or consumers, with the caveat that the proportion of such benefits in the total will be quite diverse according to the type of RI.

3.3. Demand and value of knowledge outputs

Scientists are the direct “consumers” of knowledge outputs. While new information generated at the RI is initially stored in computer memories[34] or in other technical supports, and obviously in the brains of the scientists, then it spawns a stream of specialized literature. As suggested by earlier studies (e.g. Martin, 1996; Pinski and Narin, 1976) and CBA guidelines (JASPERS, 2013; European Commission 2014) one simple empirical measure of research output is, albeit very imperfectly, given by publications (including preprints and conference abstracts).

Bibliometric techniques, analysing the patterns of the scientific literature generated over time around a research infrastructure or its experiments, e.g. through keywords, citations, and other pointers, can be conveniently exploited to associate a measure of scientific output with the RI.[35] In practice, tracking knowledge output resolves in forecasting the knowledge outputs generated by the RI scientists (taken as level 0), papers written by other scientists and citing those of the insiders (level 1), other papers citing level 1-papers, and so on. An understanding of regularities of such process is also the key factor in forecasting and ex-ante simulation, see Carrazza et al. (2014), who analyse the citation distribution of papers related to different high energy physics infrastructures over a wide time span.

For ex-ante projections, one could adopt empirical curves describing the dynamics of knowledge (identified as $S(t)$ in our CBA model) captured by publications and citations (Florio et al., 2015b). An example includes a logistic function, leading to a differential equation of the Bernoulli form:

$$\frac{dS(t)}{dt} = \alpha \cdot S(t) \cdot \left[1 - \frac{S(t)}{\beta}\right] \tag{11}$$

where $\alpha > 0$ is an instantaneous growth rate parameter and $\beta > 0$ the equilibrium limit size of knowledge growth.[36]

As mentioned, a good has an economic value if somebody's welfare increases when its availability increases. What is special in science is that the demand for the knowledge output of a RI project is driven by scientists who are often at the same time users and producers of knowledge. This does not happen for most of other infrastructure services. Passengers of high speed rail demand the transport service, but are in no way involved in its production.[37]

The fact that scientists are also the producers of knowledge offers a different way to think to the value of this output. Most scientists are paid fixed salaries and are relatively independent in the allocation of their time. Thus, when they spend some time on a research project, they have an opportunity cost, which we equal to the average scientist's hourly compensation. Hence a reasonable proxy of the value of scientific

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[30] A very selective sample includes Schultz (1961); Mincer (1974), Psacharopoulos and Patrinos (2004) and Blaug (1987).

[31] An alternative approach to instrumental variable regression models is to study education attainments and earning outcomes for siblings. This should allow to reduce or eliminate the bias caused by unobserved differences (Card, 1999).

[32] Private return is defined as the increased earning (after tax) for an individual that has achieved tertiary education net of what he/she has paid to attend the education institute, relative to the control group of people with secondary level of education. In other literature, returns to education are calculated in different and not consistent ways.

[33] The European Union Member States except Malta, plus Iceland, Norway, Switzerland and Turkey.

[34] At the LHC something like a million Gigabytes per second of information is produced, ‘sufficient to saturate every hard disc of the planet in about a day’ (Giudice, 2010: 135).

[35] These techniques are discussed by Carrazza et al. (2014).

[36] There are several versions of this simple non-linear differential ‘epidemic’ equation e.g. in the literature on innovation or mathematical biology. It has the well-known feature that the growth process is initially exponential and then slows down and asymptotically reaches a steady state (S-shaped process). Perhaps one could argue instead that the steady state will never be reached and direct citations will continue forever. Or one could suppose that, since knowledge is subject to obsolescence, after some time of stabilization there will be a decline in citations. These issues are discussed by Carrazza et al. (2014) who discuss other functional forms.

[37] There are some exceptions, that are to be found in some Non-Governmental Organisations and in local communities, or with distributed technologies as solar energy power. These exceptions are generally restricted to small scale infrastructures.

output is its MPC. This would be the time spent by scientists to make research and produce a paper, a preprint or other knowledge outputs, valued at appropriate shadow wages.[38] As argued in Section 2, this idea is consistent with standard practice in CBA and also in the way GDP is computed when the services provided by the public sector are accounted for, because of the lack of meaningful prices for such services. We obviously refer here to an abstract 'statistical' paper, as the impact of individual papers can vary considerably, from negligible to huge.

The MPC of a paper would capture only part of the total value of knowledge output. In fact, the value of knowledge is made of two components: the social value of a publication per se plus the social value attributed to the degree of influence of that piece of knowledge on the scientific community. If the former is captured by the number of papers written and valued through the MPC, the latter is reflected in the number of people that would read the paper (reflected e.g. by the number of downloads from an electronic repository) and eventually the number of citations a paper gets. Using citations as a measure of the significance of a scientific paper is an imperfect but widely accepted approach if we accept the view that – on average – citations reflect the social recognition that the scientific community acknowledges to the paper (De Solla Price, 1970; Hagström, 1965). It is therefore reasonable attributing a statistically higher MSV to a frequently cited paper in one field.[39] Then, a shadow price of citations is needed. By analogy with the MPC of papers, this could be the opportunity cost of time employed by a scientist to download, read and understand someone else's paper and decide whether to cite it or not. This time can vary from few minutes to many hours or days, depending on the type of paper, its length, topic, the experience of the citing scientist and other variables.

To sum-up: first, we need to consider time allocated and shadow wages not only of scientists directly working at the research infrastructures, but also those who use and elaborate on it to produce new knowledge, so as to capture the cumulative process of knowledge output production; second, the value of citations received should be added to the value of paper produced in the first, second, … n-th wave. As it would be an exaggeration to state that there is a one-by-one relation between knowledge units produced in the first round, and those produced subsequently, we need a decay function, for example we may simply divide the value of papers produced by outside scientists by the number of references contained in the same papers, as if each contributed in the same way to the new knowledge output.[40]

Thus, after the mutual cancellation of first round costs and benefits, the benefit of measurable knowledge output is only the value of citations that papers by RI's scientists receive, plus the total value of paper production and citations of the subsequent waves of papers. It is unlikely that the S-benefit takes a high value relative to other benefits and costs in Eq. (2), but the main social benefit here lies in the pay-back of scientific personnel cost through the valuation on the knowledge output they produce, potentially a major contribution in terms of CBA of the research infrastructure. In fact the CBA study of the LHC, a major producer of scientific literature, shows that the net direct impact in welfare terms of such publications – after the direct effect L_0 – is very small relative to other effects (Florio et al., 2015a). This is not surprising as the scientific community is relatively small compared to other social groups, and if we recall that we are only considering the publications per se, not the ultimate social value of their content which can be close to nothing or huge (in science as in fiction books).

3.4. Outreach and direct cultural impact of RI

Many RIs regularly conduct a programme of outreach events and services aimed at informing the public on advances in science and technology. The RI's site may be the destination of 'science tourism' attracted by permanent or temporary exhibitions, guided tours, special events, open days, lectures and workshops. Even relatively small facilities attract visitors. For example, according to the UK Science and Technology Facilities Council (2010) since 1995 the Daresbury laboratory has committed an increasing volume of resources to public outreach activities at the local and regional levels. This produces every year a flow of about 3000 visitors, and, additionally, 3000 school students per year are involved in ad hoc programmes and activities either at the Laboratory or by the Laboratory's staff at schools. The cultural impact of Big Science projects can be much larger. The US air force area of Cape Canaveral is probably the most popular RI. The Kennedy Space Center (KSC) Visitor Complex offers a variety of attractions, like the Rocket Garden, a 3-D theatre, exhibits of artefacts and robots, a memorial dedicated to astronauts, visit to the Space Shuttle Atlantis, activities simulating the astronaut training and much more. It also offers close viewing of NASA rocket launches. The Complex is one of Florida's most popular tourist destinations and it hosts more than 1.5 million visitors[41] per year from all around the world at an admission fee of USD 43 for adults and USD 33 for children.[42]

There are standard CBA approaches to evaluate cultural tourism to museums or other recreational activities, like visiting a natural park. We suggest exploiting these methods for scientific tourism at RIs. These approaches usually rely on the estimation of the WTP, $Wx = W_1, W_2 \dots W_X$ for each type of outreach activities ($x = 1, \dots, X$) by the general public and by type of beneficiaries ($g = 1, \dots, G$): these may include visiting the RI project, its website, using the social media related to the RI, accessing other media, and including exposure to broadcasting, news and reports in the press. Hence, we can express the benefit of outreach activities as follows:

$$C = \sum_{x=1}^{X} \sum_{g=1}^{G} \sum_{t=1}^{T} \frac{1}{(1+r)^t} \cdot W_{\text{xgt}}. \tag{14}$$

Each element x requires forecasting and valuation. The travel cost method is a well-established approach for valuing the WTP of people for a desirable good, in this case a visit to the RI.[43] It consists in evaluating a good through the full travel cost incurred in its consumption, including the cost of trips (fuel, train or airplane ticket, etc.), the opportunity cost of time spent in travelling, and the cost of accommodation, food, and souvenirs. Given the number of visitors to the site in a given time period and the marginal economic cost of a trip, the demand curve can be derived and the WTP for a visit estimated. An apportionment issue arises whenever it is reasonable to assume that a trip is made also for different reasons (multi-purpose trip) and not for visiting a specific RI. E.g. the full travel cost of people going to Florida to visit, among other things, the KSC, should not be entirely imputed to the KSC. An apportionment assumption is then necessary to account for the RI-related cultural impact, so as to estimate as far as possible the relative contribution of the RI on the total flow of visitors.

It is occasionally mentioned (e.g. COST Office, 2010) that some economic opportunities are likely to arise around the tourism demand created by the existence of the RI. Commercial and accommodation activities and other business opportunities near the infrastructure could benefit from the higher flow of customers. These non-technology driven spillovers are what are generally called 'pecuniary externalities', i.e. externalities operating through price adjustments in goods, properties and land. It is usually difficult to find a direct causal relationship between a

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[38] Skilled labour in CBA is sometimes given a high shadow wage relative to observed wage, if labour markets are distorted.

[39] This is unrelated to the evaluation of the quality of the paper, which is not a statistical measure.

[40] Abt and Garfield (2002) analysed 41 research journals and found that the number of references is generally between 20 and 70 for biochemistry and molecular biology, between 20 and 50 for physical sciences and between 5 and 60 in medicine. Also, they noted that there is a linear relationship between the average number of references and the normalised paper lengths.

[41] http://media.kennedyspacecenter.com/kennedy/quick+facts/.

[42] Tax excluded (http://media.kennedyspacecenter.com/kennedy/quick+facts/).

[43] See Florio (2014) for a review of methods to estimate the willingness to pay for a good.

project (of any type) and price adjustments, so that this kind of wider effects is generally not accounted for in a social CBA. Also due to the limited relevance of this effect for the majority of research infrastructure projects, our suggestion is usually not to value it.

Besides visits in person, participation to activities on social media, television audience and website visiting are further indicators of the size of the cultural impact produced by the RI, also to be included in the term W_{xgt} of Eq. (14). These can be forecasted through proper techniques commonly used by marketing specialists, e.g., via the number of 'tweets' or followers in Twitter, posts or pages in Facebook, subscribers of the YouTube dedicated channel or number of views of a video, the estimated number of people watching an event on TV, number of blog conversations, analysis of the volume of web traffic, and registrations on the RI official website.

Revealing the tacit WTP for social network sites has been receiving increasing attention. Westland (2010) stated that when a network reaches a certain critical mass a WTP for network membership arises. Han and Windsor (2011) found that the trust generated from social activities favourably affects trust in business transactions on social network sites, thereby influencing users' WTP. Vock et al. (2013) modelled the willingness of social networks' users of paying a premium fee for benefitting of upgraded services, compared to regular membership for free, and found that social capital and the perception of people as being bonded together in a coherent unit[44] result in specific values for members, which in turn positively affect their willingness to pay (if any, see Crosbie, 2002 or Chyi, 2005 on difficulty of empirics in this area).

Difficulties in obtaining values of WTP through contingent valuation have been experienced in the cultural sector too (Snowball, 2008). In this context, the choice experiment or conjoint analysis methods are considered more useful than traditional contingent valuations. While based on stated preferences, these techniques imply asking a sample of population to choose or rank different combinations of attributes of the same good (a museum, an archaeological site, etc.), where price is included as an attribute. This enables a more effective assessment of preferences in terms of willingness to pay both for each attribute and for the whole good. The same techniques could be usefully exploited also to our purpose, in order to attempt to value the public interest for the RI.

A direct extension of the travel cost method is to focus on marginal cost of using the media, which is mostly given by the opportunity cost of time. Thus, information on incomes of users and time they spend on outreach activities, would provide a reasonable estimation of the benefit, when the WTP is not available. The LHC case study (Florio et al., 2015a) suggests that for highly visible RI the benefit flowing to the general public from outreach and the media can be substantial, as assessed ex-post. Making forecasts in this area may be difficult, but in principle it is not more difficult than the assessment of any large-scale cultural project or event.[45]

3.5. Services provided by the RI to third parties and consumers

Many RIs, particularly in applied research, provide services to users outside the scientific community in such fields as energy security and efficiency, climate change, environmental pollution, health, testing new materials and technologies. For these benefits it is in principle possible to identify a demand by the ultimate beneficiaries of the services provided by the RI. For example, for RIs whose objective is to test new methods to address environmental risks (soil erosion, floods, etc.), beneficiaries of applications of new knowledge created at the RI are all people who would enjoy an improvement of social welfare because of the risk reduction.

The main method to value these benefits is based on the WTP for a reduced exposure to risks, thus nothing really new is needed in the CBA methods to be used, drawing from CBA of environmental services (Pearce et al., 2006). In some cases, the avoided cost approach can be applied to value economic benefits: by making available a new technology or product to third parties, the RI allows those actors to save at least part of the development and testing cost.

Another example is offered by software for computing or big data management, developed for the purpose of experiments carried out at the RI but which are then released to the public and find application in other fields, e.g. in the finance sector (see Florio et al., 2015a for open source software at the LHC). Other typical examples of RI services can be found in the health field. Research targeted to improving human health by testing new drugs or new forms of treatment can benefit all those people who will enjoy higher life expectancy or quality thanks to the application of the more advanced and effective therapy. Such research is going to have an expected impact in terms of life-years saved suitably adjusted by the quality of life, for which valuation there is a well-established CBA approach. Following the literature, the monetisation of an increase in the life expectancy encompasses the estimation of the number of quality adjusted life years and the related Value of a Life Year (VOLY). Different methods of measuring or approximating society's willingness to pay for reducing the risk of death exist, ranging from contingent valuation survey to benefit transfer, from cost of illness to human capital approach (see, for instance, Viscusi and Aldy, 2003; Ashenfelter, 2006; Sund, 2010; OECD, 2012).

In the case of health RIs, unsurprisingly, preliminary empirical testing in the CNAO case (Pancotti et al., 2015) shows that the magnitude of the *A*-benefit is by far greater than any other item in Eq. (2). In contrast, for applied research, the *S*, *H*, and *C* effects are much contained relative to the *A*-effect (while the *T*-effect is largely variable across fields).

For applied research projects, in many case the consumer would eventually benefit from innovation because in competitive markets the increased productivity is passed to the consumer in the form of lower prices for the same quality, or higher quality for the same price. The estimation of such impacts is on a case by case basis, with possibly energy saving innovation the most actively researched field.[46]

3.6. The non-use value of discovery: a pure pubic good

In the previous sections we discussed the use-benefits (B_u) and costs, but have left aside B_n, the non-use term in Eq. (1). In most cases for applied research all this is enough to justify a well-designed RI, or in any case to adequately assess its NPV. However, for infrastructures for basic research we would grossly underestimate the whole impact of scientific enterprises.

As we have shown, when we guess that NPV_{RI}-$B_n = NPV_u > 0$, in most cases for practical evaluation purposes there is no need to go further in the analysis. One should just assume that B_n is non-negative, and no more is needed. If $NPV_u < 0$, it should be considered that NPV_u is only a part of $NPV_{RI,}$ thus a negative NPV_u does not mean that the society loses with the RI, but it is a signal that we cannot be content with just a guess that B_n is non-negative. In order to define more precisely B_n in Eq. (5), we adopt an approach and a terminology borrowed from environmental economics. In the framework of environmental CBA, any good or natural resource can be assigned a total economic value (Pearce et al., 2006), which in turn can be decomposed into two general classes: use value and non-use value. Use value refers to direct or indirect benefits arising from the *actual use* of an asset (e.g. using a water reservoir for energy production) or its potential or *option use*, indicating

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[44] This is what the authors define 'entitativity'.

[45] E.g. for the EXPO 2015 in Milan with an initial forecast of 20 million visitors and a preliminary outcome of around 21 million. Ansa (www.ansa.it) retrieved on October 29, 2015.

[46] See for example the Horizon 2020 Work programme 2016–2017 'Secure, clean and efficient energy' (http://www.eurida-research.com/downloads/draft_wp-sc3_energy_2016-2017.pdf).

the value attached to future opportunities of the goods (e.g. possible recreational use of the water basin). Estimating the option value usually implies that the possible present or future use is already known. We have not explicitly discussed the option value of the RIs because this concept is closely related to risk analysis, a topic that we do not develop in this paper. If an option value can be estimated, it is a use value in our framework, because it refers to future use, for which a probability distribution function can be assumed.

Non-use value denotes instead the social value of preserving a natural resource compared to not preserving it, regardless of its actual or potential (known or unknown) use. Non-use value can be translated into a *bequest value*, arising from the desire to preserve certain resources for the benefit of future generations, or an *existence value* related to knowing that a good (e.g. an animal species in danger of extinction) simply exists even if it has not actual or planned used for anyone, and independently of any altruistic motives. When a practical use of a good cannot be excluded but is still unknown, the good has a '*quasi-option* value', QOV.

The QOV concept was introduced by Arrow and Fisher (1974) when studying how the uncertain effects of some activities could be irreversibly detrimental to future environmental preservation. The QOV describes the impact of a development intervention in one period on expected costs and benefits in the next, i.e. the expected economic NPV conditional upon the realised benefits in the present period. Elaborating on this, Conrad (1980) highlighted that the QOV notion is equivalent to the expected value of information. The value of lost and new options allowed by an investment project implemented today is an expected value based on what one might learn. Pearce et al. (2006: 21) define the QOV as the 'difference between the net benefits of making an optimal decision and one that is not optimal because it ignores the gains that may be made by delaying a decision and learning during the period of delay'. In our context the QOV is the unknown loss that may occur by delaying the decision to invest in discovery. Arrow and Fisher (1974: 319) conceded that the QOV is a general notion that may be applied outside of environmental economics, as it is linked to uncertainty, information and irreversibility issues affecting decision making in general. Retaining this terminology, we argue that a RI has a QOV in the sense that it could generate discoveries that would produce positive impacts that cannot be estimated at the time when the funding decision is taken.

In contrast, the existence value (EXV) is often related to the benefit of culture, arts or sport, to which an intrinsic value is attached. Some people get utility from the mere knowledge of the existence of a cultural good, for example because of the pride they attach to heritage, despite not giving any use for it (DCMS — Department for Culture, Media and Sport, 2010: 23–24). Similarly, a scientific discovery could benefit people who have preference for knowledge. We are not referring here to scientists, but to 'ordinary' people who, even if do not fully grasp the meaning and implications of a discovery, are happier simply because they know that discovery occurred or can occur.

Hence QOV and EXV are two distinct concepts, and we can decompose B_n – at least in principle – into two separate components. We cannot rule out that in specific cases a QOV can be estimated based on 'some' information on future uses, perhaps by panel of experts in technological forecasting, but in general for a RI in basic research this would be mostly impossible. We suggest, hence, that while QOV of pure science often remains completely unknown ex-ante (and ex-post for a long time), it is prudent to set it to zero. Instead some empirical analysis about EXV could be tried.

The standard way of estimating non-use values is by stated preference techniques, based on answers given by a representative sample of the taxpayers of interest to derive respondent's tacit WTP for a good.[47] Hence we suggest estimating the WTP of taxpayers for the pure discovery potential of the RI. Conceptually the issue is not different from estimating the WTP of the general public for climate change policy or for conservation of bio-diversity. Most people have only very vague ideas about these issues, but, when – to a certain extent – they are given information, they express their attitudes in appropriately designed surveys.[48] We refer to taxpayers, even if the public good of discovery is such that virtually all the human beings have standing, because in practice any RI in basic science is supported by a state or a coalition of states, not by the universe of the potential beneficiaries. Thus it seems convenient to focus to those who in fact will fund the RI through government transfers.

Stated preference valuations of EXV include choice experiment or conjoint analysis methods, already mentioned when addressing the issue of the value of RI's cultural effects (Section 3.4). Contingent valuation has been developed as a method for eliciting market valuation of damages to environmental resources, but it has also been used to value a wide range of non-market goods and services, such as museums (Tohmo, 2004), cultural heritage (Tuan and Navrud, 2008; Willis, 1994), and local football clubs (Barlow, 2008).[49] Other methods include revealed preference techniques, which assume that EXV can be determined through the observation of economic behaviours in a related market, such as voluntary contribution to organisations devoted to the preservation of a public good (animal species, wilderness areas, etc.); or the so called 'Wellbeing Valuation' approach, based on estimating monetary values for non-use values by looking at the way a good impacts on a person's well-being, and finding the monetary equivalent of this impact[50] (for an example of application in the culture sector, see Fujiwara, 2013).

Consistently with environmental and culture economics, we advocate the empirical estimation of EXV as a benefit of RIs, in line with the Boardman et al. (2006: 229) prudent approach:

> 'Should existence values be used in CBA? The answer requires a balancing of conceptual and practical concerns. One the one hand, recognizing existence values as pure public goods argues for their inclusion. On the other hand, given the current state of practice, estimates of existence values are very uncertain. This trade-off suggests the following heuristic: *Although existence values for unique and long-lived assets should be estimated whenever possible*, *costs and benefits should be presented with and without their inclusion to make clear how they affect net benefits*. When existence values for such assets cannot be measured, analysis should supplement CBA with discussion of their possible significance for the sign of net benefits.'

Our model can be seen as an operationalization of these ideas in the field of RI. The CBA test when $NPV_u<0$ is:

$$\mathrm{EXV}_0-|\mathrm{NPV}_u|>0. \tag{15}$$

The pure subjective value of discovery should counterbalance the negative net present use-value. In other terms, the RI is deemed to have a positive measurable social impact if the (positive) existence value is greater than the net (i.e. negative NPV of measurable use-components) costs.

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[47] We have already mentioned the use of contingent valuation to derive the willingness to pay for virtual cultural activities and services provided by the RI (Section 3.4).

[48] Some criticism has been raised against the legitimacy of non-use values (Weikard, 2005; Boudreaux et al., 1999. However, the importance of existence value as a component of the total economic value of goods is advocated by contingent valuation studies and even reflected in some legislation, e.g. in the United States Federal Preservation Regulation (Dana, 2004).

[49] For example, Jura Consultants (2005) estimated that the museum, library and archive services of the community in Bolton (UK) were worth £10.4 million, of which £3 million related to non-use value.

[50] In practice, a survey is submitted to measure the effect of a public good on happiness. If a good increases happiness by 1 index point per year and additional x euro of income also increases happiness by 1 index point, then the equivalent value of the public good is x euro.

Having set a conceptual frame, we turn to possible strategies for the empirical estimation of EXV. We need to estimate the minimum amount of money that taxpayers should be asked to pay for the EXV of a potential discovery.[51] We can proceed in three ways: stated preference techniques, revealed preference techniques and benefit transfer. Under the first approach, a contingent valuation on a representative sample of tax-payers should test the WTP an amount of money equal or greater than the threshold necessary to get a positive NPV_{RI}. We can see this as a formalisation of the way scientists and policymakers often implicitly justify public spending based on guesses of social preferences. The questions & answer online site of the Earth Observation Environmental Satellite (Envisat),[52] replies to a question on the cost of the infrastructure, by stating:

> 'Envisat cost 2.3 B Euro (including 300 M Euro for 5 years operations) to develop and launch (launch price tag: 140 M Euro). This is equivalent to 7 Euro per head of population across all the ESA member states, or about one cup of coffee per year spread over its 15 year lifecycle.'

One possible objection to our suggestion is that the contingent valuation is rather costly. Nevertheless the typical cost per capita of a well-designed contingent valuation would be a very modest fraction of the overall cost of the RI in the first place, particularly for the large ones. Another possible objection is that asking individuals their WTP for the mere existence of any good may not be easy and may result to be biased by a number of individual, cultural and socio-economic circumstances (Carson, 2012; Carson and Groves, 2007). In order to address these issues, the evaluator can take into account a number of recommendations developed since the early Nineties by a panel of distinguished economists[53] for the US National Oceanographic and Atmosphere Administration (NOAA, 1993), including indications about the modalities and structure of the interviews.

As a second approach, valuation methods based on revealed preferences can be deployed. For example, the social value attributed to potential discovery can be revealed by donations in some domains. Health research, for example, is supported by voluntary giving. In some countries taxpayers can name a charity to whom a percentage of their taxable income is donated and several scientific institutions are supported in this way.[54] This suggests that a benchmark about the WTP for science (and even for different fields and topics) can be revealed by observation of actual behaviour of large numbers of individuals.

A third approach, not necessarily alternative to the previous ones, would be to recur to benefit transfer. In this case a meta-analysis of contingent valuation studies on the EXV of discovery produced by other projects is used to establish a benchmark median value or a range of values. Then the minimum per capita value that the EXV of the RI should take to compensate for the negative net use-costs can be compared with such benchmark. If it is well within the range, or in the median to lower bound of it, we can guess that the project is as beneficial as other projects for which empirical analysis of an existence value is available.

We conclude that, once the concept of the EXV, i.e. the pure value of discovery, is introduced, even if the QOV remains unknown, the NPV of RI projects in basic research can be evaluated. If the 'one cup of coffee per year' test is passed for other projects, but not for the one under appraisal, the qualitative case for saying that there is a net benefit for the society would need to be much stronger than otherwise.

4. Conclusion

Our approach to the social CBA of large-scale, capital intensive, RIs is consistent with the principles of infrastructure economics (Picot et al., 2015). On the cost side, frequently project delimitation and cost apportionment must be solved, but not differently from other contexts. On the benefit side, research is a service provided to society. As for any other service, it is crucial to estimate its demand, in a context where it is not rationed by market mechanisms. We have suggested that the direct notional demand for RIs comes from researchers and that a peculiarity of RI is that its users are also service producers. This implies an estimation of social benefits of knowledge outputs based either on the value that scientists would be willing to pay for working on the RI project, or on the MPC of knowledge, valued at a suitable shadow price. The investment cost and operating costs (excluding scientific personnel) are relatively easy to be computed. The core benefit assessment is then based on six main dimensions: impact on firms mainly because of technological spillovers based on access to new knowledge and learning-by-doing; on employees and students because of the increase of human capital; the direct social value of publications for scientists, direct cultural effects because of outreach activities, other services provided to consumers, and the willingness to pay for the pure value of discovery, a public good.

The magnitude of each of the use-effects significantly varies depending on the size of the RI, the field of research, the kind of activity mainly carried out (either fundamental or applied research) and external factors. Among these, the absorption capacity of suppliers to leverage the learning acquired by working for the RI project is crucial. A proactive, long-term approach to leveraging the spillover potential would be needed in order to maximize the benefits of collaboration between the RI and the industrial sector. A similar challenge arises with the benefit from human capital accumulation, which is bigger if the national institutions and firms that employ former RI-students succeed at making good use of individual learning and capacity, but also if the skills acquired during the training period at the RI are not so specific that could hardly be transferred in another context. Additionally, applied RIs might produce other benefits when research is linked to services to beneficiaries outside the scientific community (e.g. patients of health research facilities, the general public for meteorological or environmental science projects including advanced monitoring techniques). All these variables should be expressed in terms of expected values, to be estimated through a probabilistic risk analysis: this implies assuming certain distribution of quantities and shadow prices of capital costs, operating costs and the RI's core benefits.

The analysis of use-effects may miss a substantial part of the story: the unknown future effects of scientific discovery and its non-use value. The valuation of the latter could be attempted by means of a contingent valuation aimed at assessing the WTP of stakeholders who would fund, either directly or indirectly (through taxes), the RI project. As for the former (the quasi-option value), we suggest that it is prudential not to include it in the CBA, but just to assess it qualitatively.

The CBA model that has been discussed throughout this paper is offered as a starting point for empirical testing and further analysis on appropriate samples of RI projects. This would include appropriate risk analysis, as any forecast is prone to error (see Flyvbjerg et al., 2003). Risk assessment involves the set of qualitative and quantitative methods and procedures aimed at evaluating the probability that a given project will achieve a satisfactory performance (see Florio, 2014 for details), including sensitivity analysis, guessing of probability distribution functions of critical variables (Vose, 2008) and Monte Carlo simulation techniques to estimate the integral corresponding to the probability distribution function of the net present value, by drawing one value of each critical variable from the respective cumulative distribution function. The extracted values are plugged into the CBA model and the associated NPV is computed after a large number of iterations

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[51] At least for expected discoveries of the 'known unknown' type (see above). More difficult would be to state a willingness to pay for the 'unknown unknown'.

[52] http://www.esa.int/Our_Activities/Observing_the_Earth/Envisat_FAQs/(print). Accessed November 6, 2015.

[53] The nobel laureates (economics) K. J. Arrow and R. M. Solow among them.

[54] In Italy, this amounts to 0.5% of personal annual income.

(10,000 in the LHC case study by Florio et al., 2015a). Overall, the usefulness of the Monte Carlo approach is ultimately linked to the fact that the law of large numbers implies the convergence of the NPV empirical distribution to its 'true' counterpart, and the CBA result can be considered in probabilistic terms and the minimum, maximum, mean values and standard deviation of the NPV can be computed. There are however a number of subtle and important other issues in risk analysis of RI projects that we leave for future research (particularly potential relevance of the real option approach following Dixit and Pindyck, 1994, and subsequent extensions).

Moreover, the results of the CBA model for RIs could be strongly influenced by two important parameters that we have not discussed here: the impact on NPV of different assumptions on the length of the time horizon ($\mathcal{T}$), and of the chosen discount rate (r) and discounting function (exponential, hyperbolic or others). This is also left for future research, along with a fine tuning of the approach by experimenting it on a wider sample of projects in different domains.

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