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Forecasting the socio-economic impact of the Large Hadron Collider: A cost–benefit analysis to 2025 and beyond

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ABSTRACT

In this paper we develop a cost–benefit analysis of a major research infrastructure, the Large Hadron Collider (LHC), the highest-energy accelerator in the world, currently operating at CERN. We show that the evaluation of benefits can be made quantitative by estimating their welfare effects on different types of agents. Four classes of direct benefits are identified, according to the main social groups involved: (a) scientists; (b) students and young researchers; (c) firms in the procurement chain and other organizations; and (d) the general public, including onsite and website visitors and other media users. These benefits are respectively related to the knowledge output of scientists; human capital formation; technological spillovers; and direct cultural effects for the general public. Welfare effects for taxpayers can also be estimated by the contingent valuation of the willingness to pay for a pure public good for which there is no specific direct use (i.e., as non-use value). Using a Monte Carlo approach, we estimate the conditional probability distribution of costs and benefits for the LHC from 1993 until its planned decommissioning in 2025, assuming a range of values for some critical stochastic variables. We conservatively estimate that there is around a 90% probability that benefits exceed costs, with an expected net present value of about 2.9 billion euro, not considering the unpredictable applications of scientific discovery.

1. Introduction

Cost–benefit analysis (CBA) is widely used by governments and economists to evaluate the socio-economic impact of investment projects; it requires the forecasting of inputs, outputs, and their marginal social values (MSVs) in order to determine the expected net present value (NPV) of a project. CBA theory is reviewed for example by Drèze and Stern, 1987, 1990; Johansson, 1991; Boardman et al., 2006; Florio, 2014, and Johansson and Kriström, 2015. In this framework, a project is desirable if its social benefits exceed costs over time. This approach is well developed for conventional infrastructure and is supported for example by the World Bank, the European Commission, the European Investment Bank, the OECD, and other national and international institutions (Baum and Tolbert, 1985 and World Bank, 2010; European Commission, 2014; European Investment Bank, 2013, and OECD, 2015; for the WHO, see Hutton and Rehfuess, 2006).

Until now, the application of CBA to research infrastructure (RI) has been hindered, however, by claims that the unpredictability of future economic benefits of science creates a difficulty for any quantitative forecasts. For example OECD, 2014 (p. 12), in a recent study of the social impact of CERN, states that a qualitative approach is preferred because of possible criticism of quantitative methods. In a survey of past experience, Martin and Tang (2007, p. 15) – while noting substantial advances in empirical analysis of the different channels through which research expenditures spill over to society – conclude that it is impossible to compare the different channels of propagation of the social benefits of science, or to provide "a quantitative answer to the question of how the overall level of benefits from basic research compares with the level of public investment in such research." They suggest that quantitative forecasts would lead to underestimation of the benefits, and cite Feller et al., 2002, who report that according to survey data, "firms investing in university research do not attempt to make any cost-benefit analysis of this investment on the grounds that it would be too complex and costly."

We acknowledge that CBA of research infrastructure is complex and that there is a risk of underestimation of benefits. Nevertheless, given the importance and the increasing cost of science, the potential advantages for decision-makers of exploring new ways to measure and compare social benefits and costs of large-scale research infrastructure cannot be exaggerated.

What follows is an application of the CBA framework developed by Florio and Sirtori (2015), and Florio et al. (2016) and should be seen as a way to explore its feasibility in practice. There are two important caveats. First, we are not claiming that decisions on funding scientific projects should be based exclusively on their measurable socio-economic

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impact, as there clearly are several other considerations at stake (the scientific case itself, strategic and ethical issues, etc.). Second, our approach is conservative, because it deliberately leaves out several qualitative evaluation issues. In particular, a novelty of our approach is to make a sharp distinction between what is measurable and what is not measurable and to focus exclusively on the former. We shall show that even leaving aside what cannot be predicted in quantitative terms, including the long-term effect of a discovery, a proper CBA model can still be applied to large-scale research infrastructure with interesting empirical findings.

The Large Hadron Collider (LHC), our case study, is the biggest experimental machine in the world (CERN, 2009). This, arguably, is a stringent test of the practical applicability of the Florio and Sirtori (2015) methodology, because of the very large scale of the project, its long time horizon, its peculiar international management, and finally because the LHC's physics is basic science, at present without any predictable economic application.

The structure of the paper is the following: in the next section we briefly present the object of our analysis, the LHC, and why it poses a challenge for CBA; in Section 3 we introduce our CBA model; Section 4 briefly describes data sources and methods; Section 5 is about estimation of costs; Section 6 deals with the direct value of publications to scientists; Section 7 presents the social benefits of technological externalities; Section 8 considers the human capital effects of the LHC; Section 9 offers a forecast of the cultural effects; Section 10 enlarges the scope of the analysis to non-use benefits; and Section 11 concludes.

2. The Large Hadron Collider

The LHC is currently the largest particle accelerator in the world. A particle accelerator is a device in which particles (protons and atomic nuclei, in the case of the LHC) are accelerated and made to collide with a target or with each other, with the goal of studying the structure of matter. Particles are accelerated by subjecting them to electric fields and are collimated into focused beams by magnetic fields. Particle beams travel in a pipe in which a vacuum has been established and are brought to collide in experimental areas in which the debris from the collisions is accurately measured by devices called detectors, which allow for an accurate reconstruction of what has happened during the collision.

The main goal of the LHC is to study the precise nature of the forces that govern fundamental interactions at the shortest distances that are currently accessible, which requires the colliding particles to hit each other at the highest possible energy.

In operation since 2009, a first goal was reached with the discovery in 2012 of the "Higgs boson," at the time the only major missing piece of information in the existing theory of fundamental interactions. Current research involves both investigating the properties of the newly discovered Higgs boson and searches for deviations from the current theory, which is believed to be incomplete, and is foreseen to continue for at least about another decade.

The LHC was built by the European Organization for Nuclear Research (CERN). Construction work lasted from 1993 to 2008. The LHC is the largest element of a chain of machines that accelerate particles to increasingly higher energies—the CERN accelerator complex. The accelerator complex is developed, maintained, and operated by CERN. This facility is exploited by the experimental Collaborations that perform experiments in the areas where collisions occur. Each experiment is based on a detector, designed, built, and operated by a Collaboration that involves both the participation of CERN and of scientists from a number of institutions (universities and research labs) from several countries. Four main experiments exploit LHC collisions; the two largest ones both involve several thousand scientists from several hundred institutions in almost fifty countries. The corresponding detectors are roughly the size of a ten-story building. When observing particle collisions, the four experiments produce about 1 GB of data per second, which are either analyzed inside by LHC Collaborations or sent to a number of other computer centers around the world, connected through the worldwide LHC computer grid.

This context is particularly challenging for cost–benefit analysis for several reasons. First, this is a very large infrastructure by all measures: number of people involved, physical size, cost. Also, it has an especially complicated structure due to the intricate interplay of accelerator and detectors in the experimental Collaborations between the host laboratory (CERN) and its participating institutions, with the large number of countries and different kinds of organizations involved (universities, research labs, national academies). This poses difficult cost apportionment and aggregation issues when attempting to estimate costs and benefits.

Second, the life-span (both past and future) of the facility is quite long: this requires both retrospective evaluation and appraisal techniques, since capital costs for the LHC were incurred starting from 1993 and the generation of both operating costs and benefits are expected to continue for some years in the future.

Third, because the LHC is an infrastructure for fundamental research, the evaluation of its benefits cannot be based on an estimate of the applications of its discoveries.

In view of all this, we will argue that the application of a CBA model to the LHC is a form of validation of the model itself, in that the successful application of the model in this context guarantees that the model will be able to handle more conventional or simpler situations, such as infrastructure of a more applied nature, of a smaller scale, and with a simpler legal and organizational structure.

3. The model

In general, an investment project passes a CBA test if NPV > 0. If B_{t_i} and C_{t_i} are respectively benefits and costs incurred at various times t_i,

$$NPV = \sum_i \frac{B_{ti} - C_{ti}}{(1+r)^{ti}} \tag{1}$$

with r the social discount rate, needed to convert a future value at t in terms of a reference level at $t = 0$. We do not explicitly include an expectation operator in this notation, but all the variables should be considered as stochastic and are taken here at their mean values, given their probability distribution functions. In turn, B and C include $i = 1, 2, \ldots, I$ input and output flows, each occurring at time $t = 0, 1, 2, \ldots, T$ and valued by shadow prices reflecting their MSVs (Drèze and Stern, 1987; Florio, 2014).

In order to address the evaluation problem quantitatively, we build on the model developed by Florio and Sirtori (2015), and Florio et al. (2016) to which the reader can refer for details of the approach, including a review of previous related literature. Borrowing some ideas from environmental CBA (Johansson, 1995; Johansson and Kriström, 2015; Pearce et al., 2006; Atkinson and Mourato, 2008), Florio and Sirtori (2015) break down the NPV of an RI (NPV_{RI}) into two parts: net use-benefits, i.e., net benefits to those who "use"' in different ways the services delivered by the LHC (NPV_u); and the present non-use value of the LHC, i.e., its value for people who currently do not use its services, but who derive utility by just knowing that new science is created (B_n), such that:

$$NPV_{RI} = NPV_u + B_n = (PV_{Bu} - PV_{Cu}) + (QOV_0 + EXV_0) \tag{2}$$

The first term on the r.h.s., NPV_u, is the time discounted sum of (negative) capital and operating costs (PV_{C_u}), and the economic value of benefits (PV_{B_u}), in turn determined by asking who the direct beneficiaries of the RI are. It is an intertemporal value, i.e., it has the structure of Eq. (2). The B_n term captures two types of non-use values related to future discoveries: their quasi-option value (QOV_0) (Arrow and Fisher, 1974), which is related to any future, but unpredictable economic benefit of

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