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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; (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 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,

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

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:

$$NPV_{RI} = NPV_u + B_n = (PV_{B_u} - PV_{C_u}) + (QOV_0 - EXV_0)\,. \tag{2}$$

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 new knowledge; and an existence value (Johansson and Kriström, 2015 p.25), which is related to pure new knowledge per se (EXV_0). B_n is an instantaneous value, i.e., it refers to time $t = 0$.

In order to determine NPV_u, here, as in Florio and Sirtori (2015), we ask first who the direct beneficiaries of an RI are and thus identify four classes of benefits, related to social groups: (a) scientists; (b) students and post-docs; (c) firms in the supply chain of the LHC and other organizations; (d) general public exposed to LHC outreach activities. Starting from (a), the ability to publish new research findings is the core benefit to scientists, both project insiders and outsiders (SC); (b) benefits for students and post-docs in terms of future salary and job opportunities arise from human capital formation, because of the skills gained and the reputational effects of

their training experience at the RI (HC); technological externalities (c) are benefits to firms both in the supply chain of the project procurement and to external firms involved in technology transfer and also to other organizations and businesses that save costs because of spillovers from the research infrastructure activities (T); (d) cultural effects are enjoyed by outreach beneficiaries, including those visiting the facilities and related exhibitions elsewhere, those who access websites and social media, and those who enjoy the general media exposure of LHC activities and discoveries (CU). Costs are determined as the sum of the economic value of capital (K), labor cost of scientists (LS) and other staff (LO), and operating costs (O)[1].

Of the two components of the non-use value B_n, the quasi-option value QOV_0 is very uncertain. In principle it would include serendipity effects or any other long-term impacts that cannot be predicted now in terms of probabilities (Knight 1964). The standard definition of QOV in earlier literature is related to irreversibility (the fact that certain projects definitively change a site or some stock of resources), uncertainty of demand for alternative projects (for which probabilities can, however, be guessed), and the value of delaying a decision to acquire additional information. In fact, Johansson (1995) and Pearce et al. (2006) suggest that QOV should not be included among the benefits, but considered separately as an information issue. Moreover, the LHC is already running and our CBA is not fully ex-ante, hence there is no scope now to evaluate the option to delay the start-up or other technological options (discussed by Schopper 2009). While in certain domains and for certain research projects it might be possible in principle to compute a QOV, this does not seem appropriate for the LHC. Nobody can say ex-ante what is the use-benefit for society of (possibly) discovering supersymmetric particles or the possible direct uses of the knowledge that the Higgs boson exists. Hence the social cost of delaying such discovery is fully unknown; also unknown is the direct benefit of having generated such knowledge before it would have been possible otherwise.

We thus take QOV_0 as not measurable for the LHC; we just assume that it is non-negative and we set it to zero. This is the main conservative assumption of our method of computing the NPV. We suspect that our assumption implies an underestimation of the social benefits, but it also has the advantage of removing an immeasurable object from the analysis, an issue that would otherwise be a source of purely speculative guesses.

However, the existence value EXV_0 is measurable in principle. It is the social benefit of knowledge per se, without any direct use. This is a pure public good, not conceptually different from other Samuelsonian (non rival, non excludable) global public goods, such as the integral conservation of natural habitats, of biodiversity, or of cultural heritage, considered separately from any direct economic exploitation of the protected goods. In environmental CBA, the existence value is the benefit of preserving something known to exist (European Commission 2014, Pearce et al. 2006); in the Florio and Sirtori (2015) framework, it is the benefit of knowing that something exists.

The standard welfare economics theory for a pure public good is that it is socially optimal to provide such a good when the sum of the willingness to pay (WTP) by taxpayers is equal to the social cost of provision (Myles 1995, Johansson and Kristöm 2015). Thus, EXV can be proxied by an empirical estimation of WTP of knowledge per se by the general public. We cannot exclude the possibility that in eliciting the WTP there may be a mixture of EXV and perceived QOV, for which however the information is not available to the respondents (see Catalano et al. 2016).

[1] In principle, negative externalities and other non-market related effects should also be considered. In the case of the LHC, we assume that these are either negligible (there is no pollution arising from the infrastructure, as it is mostly located around one hundred meters underground, and is carefully inspected for radioprotection) or unpredictable to date (external impact of major accidents or decommissioning costs, as the latter would depend on technical decisions possibly taken beyond 2040).

In sum, our social accounting[2] is

$$NPV = \sum_i \frac{(SC_{t_i} + TE_{t_i} + HC_{t_i} + CU_{t_i}) - (K_{t_i} + LS_{t_i} + LO_{t_i} + O_{t_i})}{(1+r)^{t_i}} + EXV_0. \quad (3)$$

Each variable in Eq. (3) is split into several contributions determined by other variables (e.g., scientists' salaries on the cost side, or additional profits of RI suppliers on the benefit side, etc.), and it is treated as stochastic, as is further explained in the next section.

4 Data and methods

The empirical analysis supporting the evaluation of the socio-economic impact of the LHC is supported by several sources of data, which are reported in detail below in the presentation of each cost or benefit item. The main categories are: (a) accounting data and expert analysis of capital and operating expenditures, including in-kind contributions; (b) scientometric data to estimate trajectories of publications and their impact in a specific domain; (c) firms' survey data on technological spillovers expressed in terms of increased sales and cost savings, or increased profits; expert analysis of the technological content of procurement; company accounting data for industries involved in procurement; and expert analysis of the cost savings or other quantifiable effects of open source software or other technological spillovers; (d) survey data and other statistical evidence of the expected or ex-post effects on salaries of former students and early career scientists; (e) statistics about on-site visitors, web access, use of social media, exposure to traditional media, and data on travel costs, opportunity costs of time, and other information related to cultural effects; (f) contingent valuation data through survey of samples of potential taxpayers about their WTP for potential discoveries related to a specific project.

Financial costs (interest rates arising from borrowing, taxes, and other cash transfers) have not been included, as they are monetary transactions that do not create value within the society at the aggregate level. These are not welfare effects, as stated by CBA guidelines adopted by national and international organizations. They would be part of a financial analysis, which is not our objective. We have also excluded the opportunity cost of public funds, as this would be related to a marginal effect of distortionary taxation, which for international grants (the way the LHC is funded) is usually not considered. Moreover, there has been no special grant to CERN by the Member States for the purpose of building and operating the LHC, which has been funded by the regular CERN budget, loans, and—for the detectors— by a very large number of contributions, including in-kind, by CERN member and non-member states (on both issues, see European Commission 2014).

The data collection required in-depth interviews of more than 1500 people, including PhD candidates and former LHC students, non-LHC-related students in five European universities, experts at CERN and elsewhere, company managers and "head hunters" (i.e., talent recruiters of CERN students and young researchers), collection and analysis of more than one hundred documents (mostly internal CERN and Collaboration reports, but also previous technical reports and research papers), and access to different statistical databases, including the analysis of large samples of company accounts data from the Orbis international dataset (BvD).

The evidence collected has then been structured in the form of a computable model in matrix form, where each cell corresponds to a benefit or cost variable and a year from 1993 to 2025, and beyond for certain variables, such as human capital effects. Past missing data in some years have been estimated and data for future years forecast by simple models, as explained in detail below.

[2] For further details on this model, see Florio and Sirtori (2015).

While in general for past data and for minor items the baseline has been taken as deterministic, for the critical forecasts a probability distribution function (PDF) has been assigned, based either on the sample information or on expert assessment of possible ranges of values around the baseline. In practice, only some critical variables need to be treated as stochastic (European Commission 2014). For a total of 19 variables (as reported below in the relevant section) a PDF has been assumed based on expert data evaluation. To simplify computation, we often assumed that a normal distribution is adequately proxied by a triangular PDF[3] (maximum, minimum, and mode value, not always with symmetric tails), but in other cases we considered that different distributions were more appropriate. We have tested that in general using (truncated) normal distributions or other continuous PDFs within a fixed range would not significantly change our results. Finally, we have determined the PDF for the NPV as for Eq. (3) by running a Monte Carlo simulation (10,000 draws conditional on the stochastic variables).

Monte Carlo methods are the standard approach for the CBA of infrastructure (Eckhardt 1987, Pouliquen 1970, Salling and Leleur 2011, European Commission 2014, Florio 2014) as they allow estimating the expected value of the variable of interest, with the overall forecasting accuracy conditional on the residual error of the assumed PDF of the input variables and with Monte Carlo error that has limit zero for infinite draws. As some decision makers (European Commission 2014) are accustomed to consider performance variables in the form of the internal rate of return (IRR, i.e., the value of r such that $NPV = 0$) or the benefit/cost ratio, we have run Monte Carlo simulations on these variables as well. Thus, we are able to generate a conditional PDF of the NPV, the IRR, and the B/C ratio[4].

In the next sections, for each contribution on the r.h.s. of Eq. (3) we present our estimation of the corresponding present value (PV).

5 Costs

LHC costs include past and future capital and operational expenditures born by CERN and the Collaborations for building, upgrading, and operating the machine and conducting experiments, including in-kind contributions, for which there exists no integrated accounting. Three categories of costs have been considered: i) construction capital costs, ii) upgrade capital costs[5], and iii) operating costs. We have estimated CERN costs from the start (1993) up to 2025, while for the different Collaborations (having different reporting systems) we have reconstructed costs using their own financial reports, supplemented by our assumptions for years after 2013. Integrated past flows have been capitalized to $t_0 = 2013$ with a 0.03 social discount rate (in line with European Commission, 2014). Future costs have been discounted to 2013 euro values by a 0.03 social discount rate as well.

In detail, we have estimated capital and operational expenditures related to LHC as follows. Budgetary allocations from CERN to LHC have been recovered from data communicated to us by the CERN Resource Planning Department, drawing from the CERN Expenditure Tracking (CET) system (account category, type, year, program at 31 March 2014). These data cover all CERN program and subprogram expenditures in current CHF, from January 1993 to 31 December 2013. The programs include: Accelerators, Administration, Central Expenses, Infrastructure, Outreach, Pension Fund, Research, and Services. Cost for each program is disaggregated in var-

[3] While we mostly use triangular PDF for computational reasons, we have checked that our overall results are robust if we use other distributions.

[4] Details of the MC simulations are available from the authors for all the variables.

[5] Only upgrade costs related to the so-called "Phase 1" have been considered, these being sustained to optimize the physics potential of LHC experiments for operation at higher luminosity.

ious subprograms (e.g., under Accelerators there are 19 subprograms, such as the SPS Complex, LHC, LEP, General R&D, etc.). In turn, each of these items shows expenditures on materials, personnel, financial costs, and others, broken down into recurrent and non-recurrent expenditure. We have excluded financial costs (such as bank charges and interests) for the reasons explained in the previous section; we have then identified the expenditure that can be attributed to the LHC, rather than other CERN activities.

In many cases, it was necessary to estimate an apportionment share to the LHC of the expenditure for each item. To double-check these accounting data, we have interviewed CERN staff in different departments to ask whether the internal reporting actually covered all the expenditures attributable to the LHC. The results of this data collection process are provided in Table 1[6]. Some overheads are not recorded in internal reporting as being related to specific accelerators or programs. However, as the LHC to some extent increased CERN's administrative costs, given the observation of past trends before the start-up of LHC operations, we have attributed 10% of CERN Administration, Central expenses, Administrative and Technical personnel to the LHC. A sensitivity analysis of the impact of apportioning a higher share of overhead costs to LHC shows that the NPV remains positive up to a 75% share attributed to LHC, without changing any other hypothesis. We have identified scientific personnel costs of CERN from the reports of CERN Personnel Statistics, available for each year. The share of this part of the personnel every year is between 19% in 1993 and 32% in 2013. This share of costs is assumed to balance with the contribution of CERN scientists to the direct value of the LHC publications, similarly to what we assume for non-CERN scientists in the Collaborations. We discuss this assumption in detail in the next section, where we discuss the valuation of scientific output (publications and other forms).

To these direct CERN costs we have added past in-kind contributions from member and non-member states[7]. We have not included any forecasts of further in-kind contributions in future. The forecast for 2014-2025 of CERN expenditures has been communicated to us by CERN staff[8].

For the expenditures of the Collaborations, we have focused the analysis on the four main experiments (ATLAS, CMS, ALICE, LHCb), as the remaining ones (LHCf, FELIX, FP420, HV-QF, MOEDAL, TOTEM) are comparatively quite small in terms of capital and operating costs. The benefits of these experiments are also excluded from the computation of the NPV. Our sources for the main four experiments have been the Resource Coordinators of each Collaboration[9]. Forecasts of future expenditures of the Collaborations have been based on the same

[6] Current CHF values have first been accounted in constant 2013 CHF by considering the yearly change of average consumption prices from IMF World Economic Outlook (October 2013), then expressed in euros at the exchange rate 1 CHF = 0.812 € (European Central Bank, average of daily rates for year 2013: http://www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-chf.en.html).

[7] These are mainly in the form of equipment made available for free to CERN by third parties and for which in Annual Accounts (Financial Statements) 2008 (CERN/2840 CERN/FC/5337) a cumulative asset value of 1.47 MCHF is recorded, combining in kind-contribution to the LHC machine and the detectors. The attribution year by year of this cumulative figure has been done assuming the same trend as for CERN procurement expenditures.

[8] Based on the Draft Medium Term Plan 2014 (personal communication April 2 2014). Again, we have implemented an apportionment to LHC of each expenditure item. As all values were given to us in constant CHF 2014, these were first converted to CHF 2013 and then future values discounted to 2013 levels by the 0.03 rate.

[9] We have analysed the expenditure data particularly from these sources: CMS Summary of Expenditure for CMS Construction for the Period from 1995 to 2008 (CERN-RBB-2009-032); CMS upgrade status report (CERN-RBB-2014-056); Draft Budget for CMS Maintenance & Operations in the Year 2014 (CERN-RBB-2013-086); Addendum No. 6 to the Memorandum of Understanding for Collaboration in the Construction of the CMS Detector (CERN-RBB-2013-070/REV); Addendum No. 7 to the Memorandum of Understanding for Collaboration in the Upgrade of the CMS Detector (CERN-RBB-2013-127); Addendum No. 8 to the Memorandum of Understanding for Collaboration in the Upgrade of the CMS Detector (CERN-RBB-2013-128); Memorandum of Understanding for Maintenance and Operation of the ATLAS Detector (CERN-RBB-2002-035); ATLAS Upgrade Status Report

sources. When only cumulative data at a certain year were available, the yearly distribution has been interpolated linearly. In the same way, some missing yearly data for the LHCb Collaboration have been interpolated.

We have not considered the cost implications of new projects—the High Luminosity Project and of the LHC Upgrade Phase 2—as they mostly will run after our time horizon. To avoid double counting, the CERN contributions to the Collaborations have been excluded from their total expenditures. Similarly to what we assume for CERN, the scientific personnel cost of the Collaborations (paid by their respective institutes) has been taken as balancing the marginal cost valuation of the scientific publications attributed to each experiment and excluded from the grand total of cost; see the next section regarding this point.

The overall trend of cumulated LHC-related CERN and Collaboration expenditures is shown in Fig. 1. While we consider the information up to 2013 as given, we treat the forecasts from 2014-2025 as stochastic. We have assumed a normal distribution of the total future cost (2014-2025) with mean equal to[10]1.97 G€ and a standard deviation compatible with mean ±50% as asymptotic values. This range is based on in-depth interviews with experts at CERN and analysis on the most optimistic and pessimistic future cost scenarios[11].

Summing up: after including the value of in-kind contributions, we have reconstructed the time distribution of LHC costs over 1995 to 2008 (see Fig. 1), while CERN costs unrelated to LHC and costs for future upgrades have been excluded, as their benefits will occur beyond our time horizon. Our final estimate for the expected mean value of the total cost of the LHC over 33 years (1993-2025) is $\langle K + LO + O \rangle = 13.5\ G\text{€}$, net of scientific personnel cost[12]. Here and in the next sections, the mean value refers always to the outcome of the Monte Carlo process after 10,000 draws.

6 Benefits to scientists: the value of publishing

We start our discussion of benefits with one that turned out to be small, when properly measured: the benefit of academic publishing per se. In fact, the core benefit of the LHC to scientists is the generation of experimental data that sustain the opportunity to publish new research. It is important to clarify that we are not valuing here the wider social impact of the actual content of the publications, i.e., of the scientific value per se or of its future practical use (if any), but we focus only on the direct effect of publications for science insiders, a special social group.

We briefly elaborate on this issue. The paper by Peter Higgs, introducing in a short paragraph the theory of a massive boson, was published in 1964, about the same time as papers by other

2013-2014 (CERN-RBB-2014-022); Request for 2014 ATLAS M&O Budget (CERN-RBB-2013-079); Memorandum of Understanding for Maintenance and Operation of the LHCb Detector (CERN-RRB-2002-032.rev-2008); Addendum No. 01 to the Memorandum of Understanding for the Collaboration in the Construction of the LHCb detector (CERN/RBB 2012-119A.rev-2014); Status of the LHCb upgrade (CERN-RRB-2014-033); RRB Apr.2014 (CERN-RRB-2014-039); for ALICE data, the source is a personal communication (May 7 2014) comprising data such as Core Expenditure 2007-2013, Construction costs, including Common Fund, per system, M&O A-budget and B-budget. Fifteen more reports have been processed by us for the analysis of costs (a detailed list is available from the authors upon request).

[10]Here and in the sequel we will use the notation G€, M€, k€for billion, million and thousands of euro.

[11] As mentioned in the previous section, we have not included decommissioning costs as we have no reliable information on them. For the same reason, we have also not tried to forecast accidents or negative externalities.

[12] To put this figure in perspective, it would be interesting to compare it with other large-scale scientific programs. This comparison is beyond our research scope, but just to mention one figure, the yearly budget of NASA (comprising several programs) in 2014 was USD 17.6 M$ (http://ww.nasa.gov/sites/default/files/files/NASA_2016_Budget_Estimates.pdf. Thus the total cost of the LHC over more than 30 years is roughly of the same size as one year of the NASA budget.

Apportionmentshare	Apportionment share	LHC-related non-recurrent expense expense	LHC-related recurrent expense	LHC-related totalcost
Accelerators		**4,486,682**	**1,690,053**	**6,176,736**
CLIC	0%	0	0	0
CNGS	0%	0	0	0
Consolidation	100%	146,370	630	146,999
Experimental Areas PS	0%	0	0	0
Experimental Areas SPS	0^a and 50^b	2,664	50,911	53,575
General R&D	0% <2007; 50% from 2008	1,760	727	2,487
General Services	0% <2007; 50% from 2008	1,480	11,052	12,533
LEP	0%	0	0	0
LHC	100%	4,076,429	1,111,295	5,187,724
LHC injectors	100%	28,420	3,221	31,641
LHC injectors upgrade	100%	14,103	186	14,289
LHC upgrade	100%	153,252	3,218	156,470
Low and medium energy	0%	0	0	0
Medical applications	0%	0	0	0
PS complex	50%	25,242	231,207	256,449
R&D	50%	2,944	2,797	5,741
R&D CLIC	0%	0	0	0
SPS complex	50^c and 80^d	34,020	274,809	308,829
Administration		**9,325**	**314,484**	**323,809**
Administrative computing	25%	1,855	36,585	38,440
Directorate	25%	3,438	84,329	87,767
Finances	25%	716	30,729	31,444
General Services	25%	1,400	24,705	26,105
HR	25%	1,801	113,267	115,068
Procurement	25%	115	24,869	24,984
Central expenses		**268**	**91,559**	**91,827**
bank charges and interests	0%	0	0	0
Centralised personnel Expenses	25%	0	56,968	56,968
Housing fund	0%	0	0	0
Insurances	25%	0	14,111	14,111
Internal taxation	0%	0	0	0
phone and postal charges	25%	0	1,101	1,101
Storage management	25%	268	19,379	19,647
Infrastructure		**181,721**	**1,092,689**	**1,274,410**
Building construction	80%	69,728	0	69,728
Computing	20%	5,124	27,702	32,826
Energy	20%<2000, then 50%, 80% as of 2008	155	478,824	478,979
General Services	50%	0	438	438
Medical service	20%<2000, then 50%, 80% as of 2008	6,497	108,786	115,284
Site facility	40%	83,850	468,111	551,961
Technical infrastructure	40%	10,144	0	10,144
Waste management	40%	6,223	8,828	15,050
Outreach		**20,053**	**141,812**	**161,865**
Communication	80%	15,274	104,498	119,772
Exchanges	0%	0	0	0
Knowledge and Technology Transfer	50%	4,779	18,306	23,085
Schools	0%	0	0	0
Pension Fund		**0**	**0**	**0**
Pension fund	0%	0	0	0
Research		**618,001**	**2,533,356**	**3,151,357**
Computing	50^e and 80^f	23,854	71,736	257,658
Controls	80%	26	71,736	3,385
Data analysis	0^g, 50^h, 80^i and 100^l	8,959		80,695
Electronics	50%	5,498	1,192	148,102
EU supported R&D general	50%	25,572	291,565	26,763
General Services	50%	26,345	2,813	317,910
Grid computing	80%	1,447	161,380	4,260
LHC computing	100%	126,539	1,252,968	287,919
LHC detectors	100%	317,039	272,638	1,570,007
LHC detectors upgrade	100%	78,328	0	350,966
Non-LHC physics	0%	0	99,297	0
Theoretical physics	50%	4,394	17,441	103,691
Services		**3,039**	**17,441**	**20,480**
Electronics	80%	3,039	17,441	20,480
Total		5,319,088	5,881,396	11,200,484

Table 1: LHC-related costs covered by CERN by Programme and Subprogrammes and apportionment share to LHC (1003-2013; k€ at 2013 constant prices). Source: Author's elaboration based on CERN data and interviews, see main text. a= Codes EP, EPL, EPP. b= Codes ASE, ATB ESI. c=Codes FSP, RFT. d= Codes ASM FAS, RFS, TSP. e= Codes RSC, RSI. f= Codes RCE, RCG, RCL. g= Code RCX. h= Code RBD. i= Codes RDD, RDH.

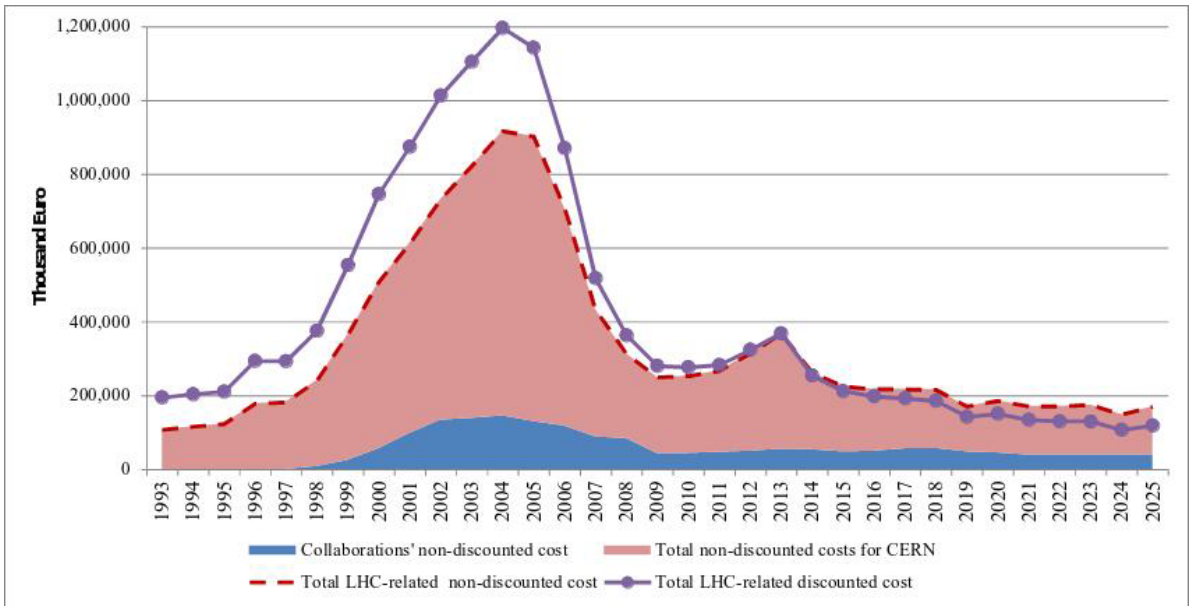

Figure 1: Time distribution of LHC costs (discounted and non-discounted).

physicists now acknowledged as leading to a similar theoretical prediction. It took nearly 50 years to confirm this intuition experimentally at the LHC. Nobody currently knows if and when the theoretical prediction of a new particle decades ago, its recent experimental discovery, and further precision measurements in future, will lead to any practical application. We know, for example, that more than one hundred years after the pathbreaking articles by Alfred Einstein (1905 and 1916), practical applications of the theories of special and general relativity, respectively, are now widespread, e.g., in any GPS device. However, this ex-post (after one hundred years) knowledge is not helpful to evaluate ex-ante the social impact of a specific publication, or of any number of publications: it only suggests that there is a non-zero chance that any substantial new knowledge will have an economic impact, which seems a reasonable assumption.

Instead, for the scientists, either CERN employees or those hired by the universities and other institutes participating in the experiments, the direct benefit of publications in principle is measurable by the track record of past publications. In this perspective, the benefit of publications is proxied by its impact on the scientific community. This benefit has a limited impact on the overall balance of the social impact of the LHC. This is not surprising because, first, the scientific community of high-energy physicists and related fields is small relative to other social groups; and because we are not including here the value of knowledge to society per se as embodied in the publication (see our discussion of non-use benefits for the taxpayers).

The observable demand to publish and to access scientific publications does not provide a set of market prices that can be used to estimate the marginal willingness to pay by science insiders. For example, the subscription prices of journals are usually paid by libraries for their users, the open source fee for some journals may be paid by research funds, many papers are available for free (e.g., the more than one million pre-prints available in the ArXiv repository for physics). The usual alternative to estimating WTP by revealed or stated preferences is the marginal cost approach to the estimation of benefits (European Commission 2014). Hence, a publication produced by LHC insider scientists (L_0) has a value that is on average equal (or not less) to its production costs (scientific personnel costs). In other words, the marginal social value of a "statistical" publication is the average marginal cost of producing such a publication.

Assuming linearity of publication production respect to time (which is well documented by the stability of the average coefficient of number of publications per researcher per year in each field—see Carrazza et al. 2014), this fact has the interesting consequence that the scientific personnel cost is balanced by the benefit of the publications. Thus, with a considerable advantage in terms of estimation of costs and benefits, the two amounts can be assumed to cancel out; and therefore neither the benefits nor the costs are explicitly included in the CBA. While some evaluator may try separately to estimate the cost and benefits (in our narrow meaning) of the publications (and similar products, such as preprints, conference abstracts, etc.) and further refine the analysis, this estimation in the LHC case would be an overwhelming task, given the large numbers of scientists involved in the experiments at any point of time (around 10,000).

Hence, we exclude from the benefits the first round of publications L_0, those from the LHC insiders, and consider then only the additional benefits arising from papers (L_1) by non-LHC scientists citing L_0 papers, with the direct benefit of further papers (L_2) citing L_1 papers in turn considered to be negligible (to be conservative), but including their citations to L_1 papers. We proxy the MSV of L_1 papers through the average salary received by an average scientist for the time spent on doing research and writing a paper. Our forecast of outputs is based on an estimate of publication trajectories obtained through a statistical model over a period of $N = 50$ years, starting in 2006. The results are summarized in Fig. 2. We explain below the procedure in detail.

The past (1993-2012) number of LHC-related scientific publications L_0 (including CERN and Collaborations) has been extracted from the inSPIRE database (http://inspirehep.net/) by Carrazza et al. 2014. The data include both published articles and preprints. Citations of these up to 2012 have been retrieved from the same source. In order to forecast the number EL_0 of L_0 publications 2013-2025, we have applied a double exponential model (Bacchiocchi and Montobbio 2009, Carrazza et al. 2014). This model is based on a calibration of the publishing trajectory of the LHC predecessor at CERN, the LEP accelerator. It takes the form:

$$EL_0(t) = \alpha_1 \alpha_2 e^{-\beta_1 (T-t)} \left[1 - e^{-\beta_2 (T-t)}\right], \tag{4}$$

- $\alpha_1 = 65000$ is the expected total number of authors of publications during the entire time span considered;
- $\alpha_2 = 2$ is a proxy of their productivity;
- $\beta_1 = 0.18$ and $\beta_2 = 0.008$ are two parameters determining the shape of the curve, based on the observed pattern of publications related to the LEP;
- $T = 50$ is the total number of years;
- $t = (0, \ldots, 50)$ is the number of remaining years from 2006, the start year of estimations, to the end of the simulation period (2056).

All the parameters are estimated from the data, except β_1 and β_2 .

The forecast of the number of L_1 publications over the years 2013-2050 has been based on observed pattern of average number of citations per paper (inSPIRE data), without assuming any new spike after the one related to the discovery of Higgs boson. This is again a conservative assumption, because it amounts to saying that nothing of importance will be discovered by the LHC until 2025.

We have then estimated the citations to L_1 papers by L_2 papers. Again, the number of L_2 papers until 2012 is based on inSPIRE, while to forecast 2013-2050 we assume 4 citations per

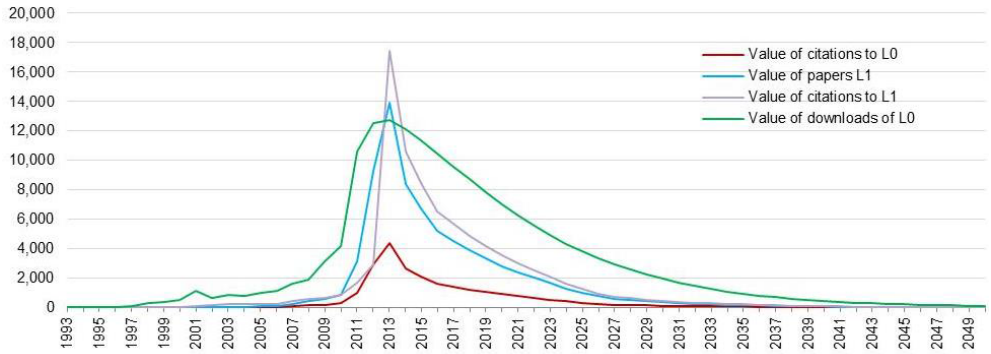

Figure 2: Economic value (constant k€ 2013) per year of citations to L_0 and L_1 papers; value of L_1 papers; value of downloads of L_0 papers.

paper, in line with the previous years. To these figures we have added total arXiv downloads for the field of High Energy Physics[13], which we used for 1994-2013, while in order to forecast until 2050 we have assumed the same average in future as the past (64 downloads per paper). This average number of downloads has been applied to L_0 papers.

To sum up, the direct benefits for insiders of the science community are thus: the value of L_1 papers; the value of L_1 citations and downloads to L_0 papers; and the value of L_2 citations to L_1 papers. As mentioned, the value of L_0 papers cancels out their production cost and it is not included. The value of L_2 papers and beyond, and citations to them, is considered to be negligible. All values are discounted at the 3% social discount rate.

After the baseline estimations, risk analysis has been performed on the total PV of the publications. To perform a Monte Carlo simulation, a PDF for the following variables has been assumed: number of references to L_0 papers in papers L_1; percentage of time of scientists devoted to research papers produced per year per average salary of non-LHC scientists; time per download time per citation.

The resulting total present value of the publications has a mean 277 M€. The value of publications (net of L_0) per se pays back only a tiny fraction of around 2% of the total cost (net of scientific personnel costs).

7 Benefits to students and post-docs: human capital formation

We have estimated that beneficiaries of human capital formation (Schopper 2009, Camporesi 2001) at the LHC over the time period 1993-2025 include nearly 36,800 early-stage researchers (ESR): around 19,400 students and 17,400 post-docs (not including participants in summer schools or short courses). Consistent with the literature on marginal returns to education (see, e.g., Harmon 2011) the benefit arising from ESR experience at the LHC is valued as the present value of the LHC-related incremental salary earned over the entire work career (see Fig. 3). This effect obviously is not the full future salary of former ESR, but it is an estimation of the LHC "premium" effect on future earnings.

We have considered five types of ESR: CERN doctoral students; CERN technical students; CERN fellows; users under 30 years; and users between 30 and 35 years. The sources of data are the yearly reports of CERN Personnel statistics from 1995 until 2013. We have estimated the number of incoming students year by year for each type and average stay, based on past data

[13] Data have been provided to us by Cornell University Library upon request.

available at the CERN Human Resources Department and from interviews with staff. Future incoming student flows have been extrapolated from past trends and checked with CERN. The HR Department records all types of students and post-docs, but we need an apportionment of these flows to the LHC. We have computed such apportionments with data from the Collaborations and additional interviews at CERN, leading to the following estimates: 30% of the total flows (for the period 1993-1998); 50% (1999-2001); 70% (2002-2007); and 85% (2008-2025). The resulting figures have then been attributed to each of the five types, based on the historical distribution, in order to derive the flow of annual incoming students over the years 1993-2025.

Ideally, in order to estimate the economic benefit to each of these types of ESR, we would have needed a sample of former LHC students of different cohorts in their present occupation and a control group of non-LHC peers. However, given that most of the actual flows of incoming ESR at the LHC occurred in recent years, i.e., after the startup of experiments in 2008, the latter information is not available. Hence, our strategy was to make an estimation based on two samples, respectively of current and former students and post-docs. A survey, directed at both students and former students, was performed between May and October 2014 and in March 2015 through an on-line questionnaire and direct interviews at CERN. The details of the survey, including the questionnaire, are available in Catalano et al. (2015a). The survey strategy was to elicit both expectations of current students at the LHC and evaluations from former students, now employed in different jobs, including outside academia. Information from 384 interviewees coming from 52 different countries has been collected: 75% of respondents are male; 38% are 20-29 years old, 43% are 30-39 years old, the remaining are more than 40 years old; 65% of respondents are related to the CMS Collaboration and 22% to ATLAS, while the remainder are in other experiments or LHC-related research at CERN. Each respondent has answered questions on a number of individual characteristics, his/her perception of the skills acquired at the LHC, and finally on an ex-ante (students) or ex-post (former students) perceived LHC premium on their salary. We assume that former ESR have some knowledge of job market opportunities and can compare their expectations with those of their peers. We have found that the two sample averages for the premium effect are strikingly similar, as can be seen in Fig. 3. This suggests that information on job opportunities and salaries is widespread and convergent (this is, after all, a relatively small international network of young researchers with close formal and informal linkages). Given that the former ESR at the LHC have gained actual experience of the post-LHC career market, we have focused on the premium declared by the respondents who have already found a job: the sample average is equal to 9.3% .

This percentage premium has been applied to the average annual salary at different experience levels, retrieved from the Payscale database. In particular, we have classified salaries by experience level (entry, mid-career, experienced, and late career) for different jobs in the USA[14] grouped in four broad sectors: industry, research centers, academia, others (the latter including, for instance, finance, computing, and civil service). A distribution of the number of CERN students across these broad sectors has been retrieved based on earlier work by Camporesi (2001) and other sources[15]. The four aforementioned career points have been interpolated with a logarithmic function.

Given the average salary in each broad sector, the LHC premium declared by interviewees, and the above-assumed shares of students finding a job in each sector, we have computed a job effect component of the human capital formation benefit. Considering that the difference

[14] See, e.g., http://www.payscale.com/research/US/Job=Electronics Engineer/Salary)

[15] For CERN technical students we have assumed that only 10% will go either to research centres or in academia, and 45% respectively in the other two sectors; for the other students, we have assumed a destination in research and academia for 60% and 20% each for the others. Interviews with experts (including "head hunters" who regularly monitor the CERN students) have confirmed this distribution.

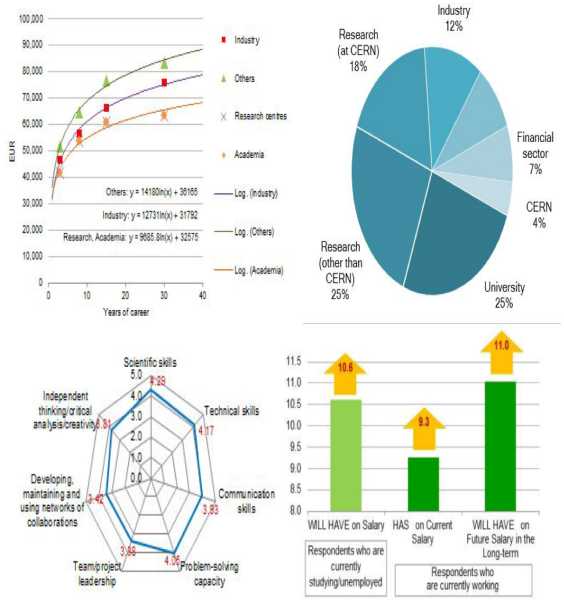

Figure 3: Top: types and number of people benefitting from training at the LHC, historical data and forecasts. Centre: estimation of future average salaries (left); current employment sector of CERN alumni (right). Bottom: perception of skill improvements due to the LHC experience (left); percentage impact on salary due to the LHC experience estimated by current students (light green) and past-students (dark green) (right).

between the pay in research and academia and the two other sectors combined is between 13% and 18% (increasing with the level of experience), and that 14% of the former students who have participated in the survey have been diverted to better-paid jobs in industry or other sectors (consistent with earlier findings by Camporesi 2001), an additional small premium of between 2-3% (triangular PDF with average and mode both equal to 2.5%) has been applied, because of the composition effect across occupations. The resulting combined 11.8% premium has been attributed to an average student over a career spanning 40 years, with the implication, for example, that the cohort of 2025 students will enjoy the benefit up to 2065. Interestingly, this figure is well in the range of the returns to higher education in the literature (for a review of more than 50 years of empirical research, see Montenegro and Patrinos 2014, who find the highest returns for tertiary education). The total number of ESR, in turn, has been taken as a triangular PDF with maximum and minimum equal to ±15% of the mode and mean, based on available data. All values are discounted, which, because of the long time span, roughly halves the cumulative benefit in comparison with its undiscounted value.

The resulting mean value of the corresponding benefits is $\langle HC \rangle = 5.5\ G\ €$. This social benefit pays back 41% of the total LHC social cost and this is the largest component on the benefit side.

8 Benefits to firms and other organizations: technological spillovers

There are two main types of beneficiaries of LHC on the business side: firms in the procurement chain, because of learning-by-doing effects; and other firms or professional organizations acquiring

knowledge for free. In both cases, these effects can be described as externalities related to the transfer of knowledge to third parties outside or beyond any contractual relations with the CERN.

Profits to firms directly arising from procurement to CERN are part of the LHC costs and are not considered a social benefit (assuming that there was no idle capacity in the firms). Thus, the benefits to LHC-related supplier firms consist of incremental profits gained through additional sales to third parties, after the procurement contract with CERN, thanks to technology transfer and knowledge acquired "for free." Such effects become particularly important the more co-designed is the technology, particularly because CERN almost never patents its own inventions, a famous example being the World Wide Web (Schopper 2009, Boisot et al. 2011). We have briefly mentioned in section 2 the scope and scale of technological innovation related to building and maintaining the LHC, in collaboration with a large number of firms involved (more than 1500, see below).

We have estimated the incremental profits based on LHC-related procurement orders (categorized according to activity and technological intensity codes), which we forecast up to 2025, and then used these values to determine incremental turnover for the suppliers through estimates of economic utility/sales ratios from Bianchi-Streit et al. 1984 and Autio et al. 2003 (based on surveys to CERN suppliers) and EBITDA margins data (a measure of gross profits/sales ratio) for companies in related sectors, extracted from the ORBIS database (BVD) of companies balance sheets[16] (see Fig. 4).

We explain here the estimation process in some detail. The total value of CERN procurement by year and by activity code has been recovered from the CERN Procurement and Industrial Services Companies (personal communication, October 2013). A sample of 300 orders exceeding 10,000 CHF in nominal value has been extracted from a data set provided to us by the aforementioned CERN office. Each sampled order has been classified (with the help of expert CERN staff) according to a five-point scale: 1) "very likely to be off-the-shelf products with low technological intensity"; 2) "off-the-shelf products with an average technological intensity"; 3) "mostly off-the-shelf products, usually high-tech and requiring some careful specifications"; 4) "high-tech products with a moderate to high specification activity intensity to customize product for LHC"; 5) "products at the frontier of technology with an intensive customization work and co-design involving CERN staff." An average technological intensity score has been attributed to each CERN activity code; we have classified as high-tech the codes with average technological intensity class equal or greater than 3. This led to the identification of 23 high-tech activity codes.

Procurement value has then been computed only for orders related to these codes, which turned out to be 35% of the total of procurement expenditures. This would be only 17% if we exclude orders below 50, 000 CHF and 58% if we include orders below this threshold and for other activity codes. We took a triangular distribution with average and mode model equal to 35% and minimum and maximum as the above range. A share of 84% of yearly total expenditures of Collaborations is attributed to external procurement, using the same share as CERN. This share has been used also for the future forecasts of both CERN and the Collaborations up to 2025, based on the previous forecast of cost trends.

For the Collaborations, which are known to include a significantly higher share of high-tech orders, we assume a triangular distribution of the share of high-tech procurement with average and mode equal to 58% and with minimum set to 40% and maximum to 75%, based on expert assessment. We have then identified 1,480 benchmark firms from the ORBIS database in the year 2013 and in six countries (Italy, France, Germany, Switzerland, UK, USA). These countries were selected because they received 78% of the total CERN procurement expenditure

[16] https://orbis.bvdinfo.com

between 1995 and 2013[17] . In selecting this sample, we have considered companies whose primary activity matches with the corresponding CERN activity codes[18]. After having observed the EBITDA margin sample distribution, we have computed an average (13.1%) and standard deviation EBITDA, weighted by country, and used these parameters to define a normal distribution of the EBITDA. We have then estimated the incremental turnover over 5 years by the LEP average utility/sales ratio to be equal to 3, based on the results of Bianchi-Streit et al. 1984 and Autio et al. 2003, which in turn are within the range of other studies as reported in Table 2. Based on these sources, we assumed a triangular distribution with mode equal to the mean, minimum 1.4, maximum 4.2. This ratio has been applied to the high-tech procurement of both CERN and Collaborations. We have finally computed the additional sales times EBITDA margin, thus estimating the incremental profits of firms in the LHC supply chain in other markets.

Further benefits to businesses or organizations providing LHC services come from software developed for analyzing the LHC experimental data and made available for free: ROOT (about 25,000 users in 2013 outside physics, mostly in the finance sector) and GEANT4 (used, e.g., in medicine for simulating radiation damage in DNA). The benefits of the externality are estimated as the avoided cost for the purchase of an equivalent commercial software application (ROOT) or the cost required for development of an analogous tool (GEANT4). The details of our approach are as follows.

The number of ROOT users outside the high-energy physics community were estimated on the basis of yearly download statistics of the software code[19] as well as interviews and personal communications with CERN Physics Department staff. We then forecast future trends based on extrapolations of calibrated estimates of CERN staff on the basis of past yearly downloads. This leads to a baseline forecast of 55,000 outside users in 2025. This has been taken as a stochastic variable with a triangular distribution and a range of ±20% about equal average and mode. The number of new users by year has been estimated based on data provided by CERN staff. The market prices of several comparable commercial software codes have then been analyzed. The range of avoided costs, depending on computing needs, goes from zero (if the R open-source statistical analysis code was used instead) to 17 k€ per year for a one-year license[20]. We have assumed a triangular yearly cost-saving PDF for each ROOT user, with average and mode equal to 1.5k€, minimum set to 1 k€ and maximum to 2 k€. Based on interviews with experts, we have assumed a trapezoidal PDF for the number of usage years, with two modes equal respectively to 3 and 10; minimum 0; maximum 20, based on actual data inspection. The number of users, times the avoided cost per year, is then discounted and summed to compute the PV of the ROOT-related benefit.

For GEANT4[21] we have identified about fifty research centers, space agencies, and firms in which it is routinely used (not including a substantial number of hospitals that use GEANT4 for medical applications). Out of this list, we have made a distinction between the 38 centers that contributed in some form to the development of the code versus the remaining ones. The avoided cost is based on the production cost of GEANT4 (around 35 M€ up to 2013, provided by CERN

[17] Data on procurement commitment by country provided by CERN staff, October 2013.

[18] The following NACE sectoral codes have been considered: manufacture of basic metals (24); manufacturing of structural metal products (25.1); forging, pressing, stamping, and roll-forming of metal (25.5); manufacturing of other fabricated metal products (25.9); manufacturing of computer, electronic, and optical products (26); manufacturing of electrical equipment (27); manufacturing of machinery and equipment not classified elsewhere (28); specialised construction activities (43); telecommunications (61); computer programming, consultancy, and related activities (62); information service activities (63).

[19] https://root.cern.ch/drupal/content/download-statistics

[20] If, e.g., Oracle Advance Analytics was used.

[21] http://geant4.web.cern.ch/geant4/license/

Average values	Research organization	Method of estimation	Source
3	CERN	Survey of firms	Schmied (1975);
1.2	CERN	Survey	Schmied (1982);
3	CERN	Survey	Bianchi-Streit et al. (1984)
3	ESA	Survey of firms	Brendle et al. (1980) and Bach et al. (1988)
1.5-1.6	ESA	Survey	Schmied (1982);
4.5	ESA	Survey	Danish Agency for Science (2008)
2.1	NASA (Space Programmes)	Input-Output model	Bezdek and Wendling (1992)
2-2.7	INFN	Input-Output model	Salina (2006)
3.03	John Innes Centre	Input-Output model	DTZ (2009)

Table 2: Economic utility's ratios in the literature. Source: authors based on cited sources

staff and generated using SLOCcount[22]; the total CERN contribution to this cost is estimated to be 50%. The avoided cost for the aforementioned 38 centers is reduced to the contribution they actually provided (assumed to be the same for each centre, thus 50% of 35 M€ divided by 38), while it is the full GEANT4 cost for the remaining ones. A forecast to 2025 and a yearly avoided cost has then been estimated. The total cumulated avoided cost has been taken as a symmetric triangular PDF ±30% about a mode and mean both equal to 2.8 G€.

To sum up: the total mean value of the technological benefits is $\langle TE \rangle$, of which around 62% arises from open software and the remainder from incremental profits for firms because of sales to customers other than CERN. The technological benefits pay back 39% of the total cost.

9 Benefits to the general public: visits to LHC and other direct cultural effects

There are direct cultural benefits of the LHC to the general public visiting CERN and taking advantage of its exhibitions, websites, and outreach activities, including their impact on the media. The general valuation criteria for these benefits has been the revealed preference of the WTP, estimated in different ways. The details of our estimation are as follows.

The key social groups that we have considered are: (a) onsite CERN visitors; (b) visitors to CERN travelling exhibitions; (c) people reached by media reporting LHC-related news; (d) visitors to CERN and Collaborations websites; (e) users of LHC-related social media (YouTube; Twitter; Facebook; Google+); (f) participants in two volunteer computing programs.

(a) Benefits for on-site visitors are determined using the revealed preference method (Clawson and Knetsch 1966), with the MSV of the time spent in travelling obtained from HEATCO[23] data (see Fig. 5). Data for onsite visitors since 2004 to 2013 have been provided to us by the Communication Groups of CERN and by each Collaboration. The forecast to 2025 has been extrapolated by a constant yearly value, based on the trend observed in the previous years. We have estimated an 80% overlap between visitors to LHC experiment facilities and the permanent CERN Exhibitions (Microcosm and Universe of Particles in the Globe of Science and Innovation); moreover, only 80% of visitors to CERN have been attributed to the LHC.

The value of travelers' time is based on HEATCO for each member state and for some non-members. Based on the distribution of visitors by country and mode of transportation, we have estimated an overall distribution of visitors based on the following PDF: trapezoid distribution for air travelers (minimum equal to 5; maximum equal to 45, first mode equal to 22 and second

[22] www.dwheeler.com/sloccount

[23] http://heatco.ier.uni-stuttgart.de/

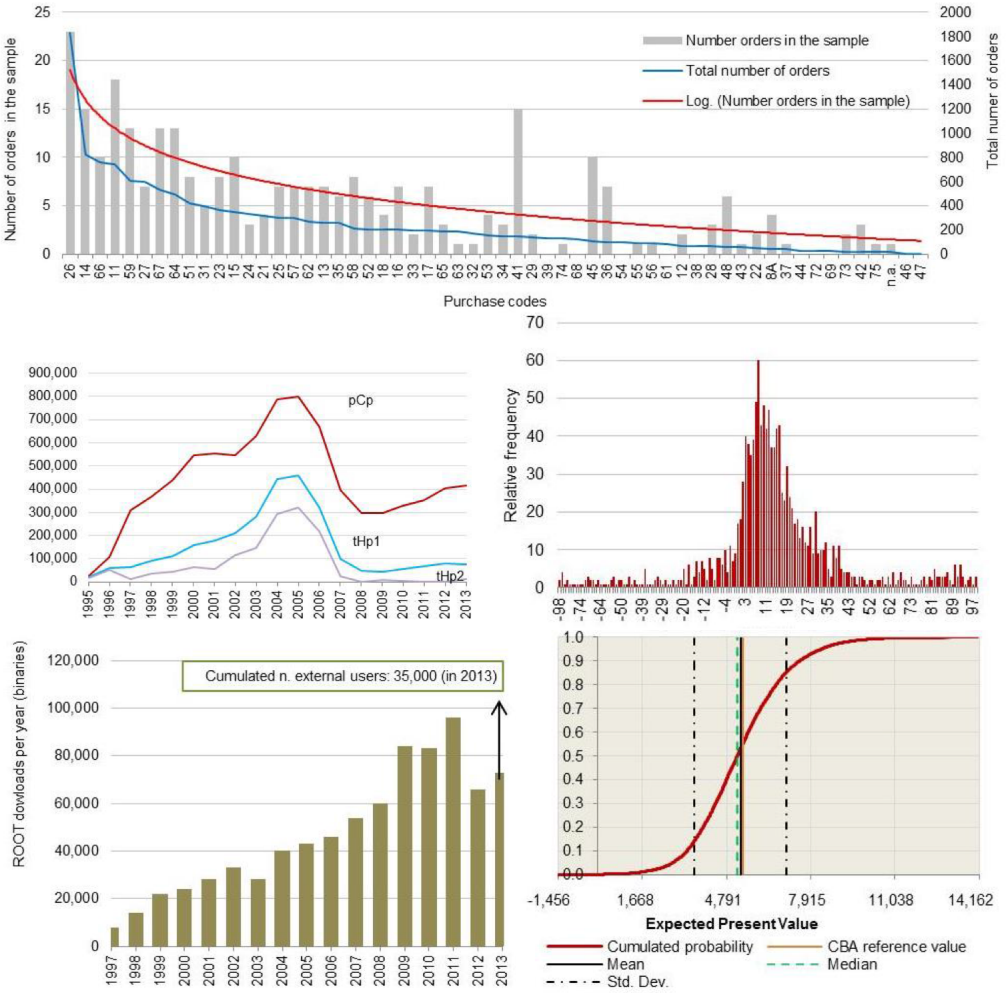

Figure 4: Top: Benefits to firms in the CERN supply chain from a sample of 300 orders by purchase code compared with all LHC orders (CERN activity codes: 11 building work - 12 roadworks - 13 installation and supply of pipes - 14 electrical installation work - 15 heating and air-conditioning equipment (supply and installation) - 16 hoisting gear - 17 water supply and treatment - 18 civil engineering and buildings - 21 switch gear and switchboards - 22 power transformers - 23 power cables and conductors - 24 control and communication cables - 25 power supplies and converters - 26 magnets - 27 measurement and regulation - 28 electrical engineering - 29 electrical engineering components - 31 active electronic components - 32 passive electronic components - 33 electronic measuring instruments - 34 power supplies - transformers - 35 functional modules & crates - 36 rf and microwave components and equipment - 37 circuit boards - 38 electronics - 39 electronic assembly and wiring work - 41 computers and work-stations - 42 storage systems - 43 data-processing peripherals - 44 interfaces (see also 35 series) - 45 software - 46 consumables items for data-processing - 47 storage furniture (data-processing) - 48 data communication - 51 raw materials (supplies) - 52 machine tools, workshop and quality control equipment - 53 casting and moulding (manufacturing techniques) - 54 forging (manufacturing techniques) - 55 boiler metal work (manufacturing techniques) - 56 sheet metal work (manufacturing techniques) - 57 general machining work - 58 precision machining work - 59 specialised techniques - 61 vacuum pumps - 62 refrigeration equipment - 63 gas-handling equipment - 64 storage and transport of cryogens - 65 measurement equipment (vacuum and low- temperature technology) - 66 low-temperature materials - 67 vacuum components & chambers - 68 low-temperature components - 69 vacuum and low-temperature technology - 71 films and emulsions - 72 scintillation counter components - 73 wire chamber elements - 74 special detector components - 75 calorimeter elements 8A radiation protection - n.a. not available). Center: CERN external procurement - commitment for total and high-tech orders (pCp: Past CERN procurement - commitment (k€ 2013) tHp1: Total high-tech procurement - commitment (k€ 2013) tHp2: Total high-tech procurement - commitment - only orders $>$ 50 kCHF (ke2013)) (right); distribution of EBITDA 2013 from ORBIS in firms at NACE industry levels matched with CERN codes (right). Bottom: ROOT download data (left); ENPV Cumulative distribution function conditional to PDF of critical variables (k€ 2013) (right). Source: Authors' elaboration of CERN data.

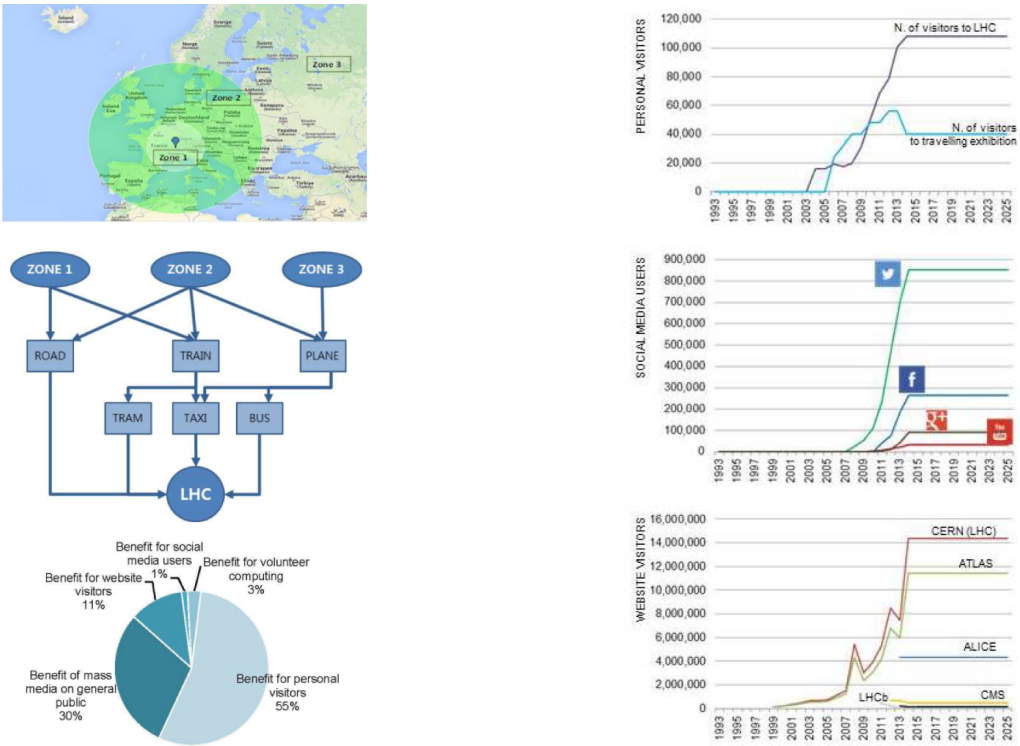

Figure 5: Left: (from top to bottom) Travel zones for CERN for visitors; CERN visitors by mode of transport; share of benefits by type of outreach activity (Cumulated impact to 2025). Right: benefits to personal, visitors, social media users and website visitors. The valuation of the benefit is based on the segmentation of visitors in three areas of origin with increasing distance from CERN (see Fig. 5), and by average travel costs for each zone, based on seven origin cities taken as cost benchmarks. For each zone, a transport mode combination and length of stay have been assumed (see Fig. 5). The three zones and the share of visitors for each zone are based on data provided by the CERN Communication Group (personal communication October 2013); additional costs have been estimated including for accommodation and meals (data extracted from the CERN website).

mode equal to 27, all in €/hour: there are two modes because of the difference between the two main origin groups and this suggests using a trapezoid PDF); triangular distribution for travel by car and train (mean and mode equal to 18; minimum 6 and maximum 30).

(b) For the CERN travelling exhibitions, we have used the number of past visitors as provided by CERN (between 30,000 and 70,000 for the period 2006-2013). We have assumed a constant number of 40,000 visitors per year during from 2014 to 2035. The WTP is prudentially assumed to be just 1 € per visitor (assuming local transport).

(c) For the benefit of LHC coverage in the media, we have conservatively considered only the news spikes on September 10 2008 (first run of LHC) and July 4 2012 (announcement of the discovery of the Higgs boson)[24]. We have estimated, based on some interviews, that the average time devoted to each LHC news per head is 2 minutes. We have treated the audience number as a stochastic variable, assuming a triangular distribution (minimum zero, maximum one billion, average and mode equal to 0.5 billion). The value of time of the target audience has been estimated based on current GDP per capita in the average CERN Member States and the USA (for 2013, using IMF data), and the number of working days per year (8 hours times 225 working days). This is treated as a stochastic, triangular distribution, with minimum equal to 3 €; maximum 42 €, and mode and mean equal to 17 €.

(d) We have estimated the number of website visitors on the basis of historical data on hits until 2013-2104 (source CERN and Communication Groups in the main Collaborations). Our forecast is conservatively based in assuming that the value at the last available observation remains constant. The benefit comes from the number of minutes per hit from users of the websites, estimated to be a triangular distribution with average and mode equal to 2 minutes, and ranging from 0 to 4 minutes.

(e) Further benefits come from LHC-related social media and website visits, with the MSV of time of the general public proxied by the hourly value of per capita GDP (see Fig. 5). For social media usage, we recovered data provided by CERN and Collaborations, attributing to the LHC 80% of the hits to CERN-related social media and 100% of those related to the Collaborations. We used historical data until 2014 and for the subsequent years we have taken the last year's data as constant. The average stay time is assumed for all social media to be distributed according to a triangular distribution with average and mode equal to 0.5 minutes per capita, ranging from zero to one minute. Time is then valued as above.

(f) Finally, some CERN projects exploit computing time donated from volunteers to run simulation of particle collisions, with WTP revealed by time spent. Two such LHC-related programs are SIXTRACK and TEST4THEORY, where outsiders donate to CERN the machine time and capacity of their own computers and are then able to access some data and to join a social network. The stock number of volunteers in 2013 has been provided by the CERN PH Department (personal communication); based on this information, we have assumed a rate of increase from the program start years (respectively 2007 and 2001). A forecast of the future volunteer stock has been given to us to 2025 by the same source; again, we have assumed a yearly rate of change over the years 2014-2025. The opportunity cost is the time to download, install, and configure the programs (15 minutes per capita *una tantum*) and the time spent in forum discussions (15 minutes per month per capita). Again, time is valued as above.

The total mean value of the above mentioned cultural effects is $\langle CU \rangle = 2.1$ G€. This value contributes around 16% against the total cost.

[24] Sources for these point estimates are: New Scientist (2008) and http://cds.cern.ch/journal/CERNBulletin/2012/30/NewsArticles/1462248

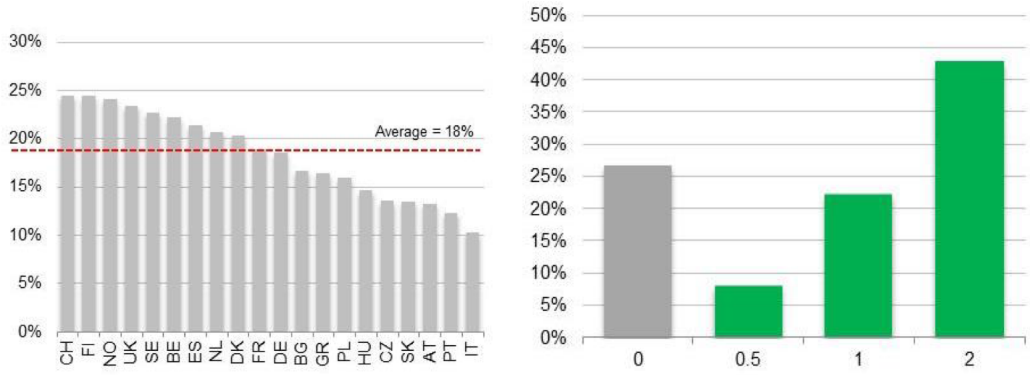

Figure 6: Share of adult population (18-74 years old) with at least tertiary education (left); average annual WPT of the respondents to the survey (right).

10 Non-use benefits: scientific knowledge as a public good

As mentioned in section 2, beyond the direct benefits accruing to certain social groups, there is a non-rival and non-excludable benefit, i.e., a public good arising from the LHC's discoveries. This is not connected to any specific use of such discoveries, but only to the social preference for knowing that such new knowledge will be available; this is a non-use value:

"A resource or a service might be valued even if it is not consumed. Such values are referred to as *non-use values*, bur sometimes they are labeled *passive-use* or *intrinsic values.* ... If the project being evaluated affects non-use values this should be reflected in the cost-benefit analysis ... among these are *existence values*" (Johansson and Kriström, 2015, pp 24-25).

The empirical estimation of non-use value in environmental and cultural economics is generally based on contingent valuation approaches and their variants. The issue is discussed in some detail in Florio and Sirtori (2015). The benchmark methodology in the literature is the NOAA 1993 panel (Arrow et al. 1993), but there have been several advances since then (see Carson 2012 for a review and Johansson and Kriström, Ch. 9). We wish to determine social preferences for the non-use value of LHC discoveries, a public good with yet unknown practical use.

We have thus designed a contingent valuation study tailored to our problem. Ideally, a random sample of taxpayers in the CERN Member States and in other countries (e.g., notably the USA) supporting the LHC in different forms would be needed. An in-depth survey, as recommended by the NOAA panel, needs personal interviews of a representative sample of the population, but in our case spreading a manageable sample across many countries and types of individuals would be too costly and not necessarily more reliable than performing a more focused survey. Hence, we have targeted university students for in-depth personal interviews in four CERN Member States as representative of future taxpayers with tertiary education. Referring to students in experimental economics and political science is common practice (see, e.g., Druckman and Kam 2011). In fact, to be conservative, we have assumed that all taxpayers with less than tertiary education would be willing to contribute nothing to scientific discovery by the LHC as a pure public good. Surely, in this way, we grossly understate the social preferences, as at least some people with less than tertiary education may have a positive WTP. The results were used to guess the WTP of taxpayers with tertiary education in CERN Member States and from non-Member States.

This survey on WTP for the LHC-related public good was undertaken in Milan in October-November 2014 and in Exeter (UK), Paris (France), and A Coruña (Spain) in February-March

2015: 1027 questionnaires were collected. The average time spent answering the questionnaire (28 questions) was about 25 minutes[25]. The respondent was first given a one-page summary of the LHC Wikipedia page as an information set. The geographical distribution of respondents was 40% from Italy and 20% each from Spain, France, and the UK. Out of the total number of respondents, 85% were 19-25 years old, while the remainder were more than 26 years old. Out of the respondents 57% were females. A share of 64% were in the humanities and social sciences, with the remainder in science-related curricula. Questions included: household composition, family income, personal income, high-school background, previous knowledge of research infrastructure, source of information, if any, on the LHC and the Higgs boson discovery, whether the respondent has ever visited CERN, interest in science, willingness to pay for LHC research activities a fixed lump-sum or a yearly economic contribution over 30 years, in pre-set discrete amounts (zero, 0.5, 1, 2 €)[26]. Only answers to the last question (yearly contribution) are used here, while all the other variables have been used for a detailed statistical analysis by Catalano et al (2016).

We have then taken the sample average yearly WTP, weighted by the number of respondents by country, for only those respondents who declared a positive annual WTP, these comprising 73% of the total. This has given us a sample distribution with three discrete values (0.5, 1, and 2 €), and mode and maximum equal to 2. Each annual WTP has then been multiplied (undiscounted, as this is an instant variable) by 30 years. This per capita WTP has been applied to 73% of respondents between 18-74 years of age with at least tertiary education coming from CERN Member States, determined by data from Eurostat 2013 (see Fig. 6). We have then added to the previous target population an additional 21% from CERN non-member states, reflecting the share of onsite visitors to CERN from non-member states (visitor statistics provided by CERN staff as a personal communication). We have treated the per capita WTP as a stochastic variable, assuming a truncated triangular probability distribution with maximum and mode equal to 2 € and minimum equal to 0.1 €, reflecting the sample distribution for non-zero values.

The undiscounted mean non-use value is found to be $\langle EXV_0 \rangle = 3.2$ G€, paying back around 24% of total costs.

11 Summary of results and concluding remarks

Based on the forecasts of social costs and benefits in the previous sections, we have determined the probability distribution of the net present value of the LHC as for Eq. (3) by running a Monte Carlo simulation (10,000 draws conditional to the PDF of the nineteen stochastic variables mentioned above[27]). Each draw generates an NPV estimate in a state of the world supported by a random set of the possible values taken by the model stochastic variables. The number of variables we have considered for the Monte Carlo simulation and the number of draws are largely in excess of what is usually done in the evaluation of large-scale investment projects by international and national bodies (Florio 2014, OECD 2015), e.g., for high-speed rail infrastructure that faces considerable uncertainty and optimism bias (Flyvbjerg et al. 2003). While we have been prudent, and even pessimistic, in our assumptions, caution is necessary in the interpretation of the final results, which we will briefly summarize and discuss here. As with any forecast covering

[25] For the questionnaire and other details, see Catalano et al. 2016.

[26] As we did not consider a higher range of values, this truncates the right tail of the distribution in such a way that in fact we are underestimating the WTP. To double-check the preferences, the questionnaire included also a question on the WTP a lump sum contribution of 30 euros in a "referendum-like" format, as recommended by the NOAA panel and in Catalano et al. (2016); we use this alternative "referendum" question format to double-check the results reported here.

[27] The full list and details of the simulations are available upon request.

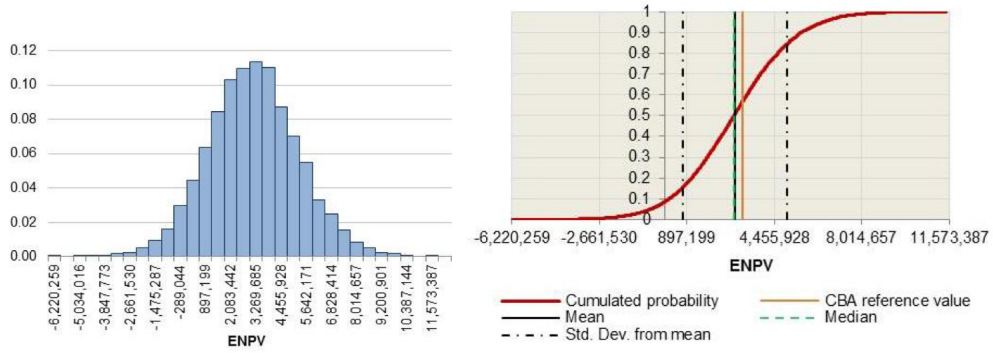

Figure 7: Net present value PDF (left) and cumulative distribution (right).

the long run, there is obviously some residual uncertainty, but we are confident that residual estimation errors are mostly in the direction of underestimating the net social benefit of the LHC. This was deliberate, as we have preferred to be conservative.

The total present value to 2025 of operating and capital expenditure of the LHC is estimated at 13.5 G€ (net of the cost of scientific personnel). In terms of contributions to the sum of the social benefits (16.4 G€), the present value of the human capital effects and of technological spillovers are the most important ones, and of similar size, each contributing around one third of the benefits. Adding the tiny secondary effect of the publications (net of the direct value of LHC research outputs), around 68% of the socio-economic benefits is related to professional activities (within firms, academia, and other organizations), while the remaining benefits spill over to the general public, either as a direct cultural effect (a private good) or as a pure public good (a non-use benefit). Any other (if any) unpredictable social benefits of future applications of scientific discoveries at the LHC are excluded from our analysis; they will remain as an extra bonus for future generations, donated to them by current taxpayers.

The final PDF and cumulative probability distribution for the NPV are shown in Fig. 7. We find that the expected NPV of the LHC is around 2.9 G€, with a conditional probability of a negative NPV smaller than 9% with a 3σ Monte Carlo error below 2%. The expected benefit/cost ratio is around 1.2 and the expected internal rate of return is 4.7% [28].

We have thus shown how a social CBA probabilistic model can be applied to evaluate a large-scale research infrastructure project, based on empirical methods. The main novelty of this contribution is that we show the feasibility, following the Florio and Sirtori (2015) approach, of a quantitative valuation of the socio-economic impact of such infrastructure in a way consistent with first principles of applied welfare economics. The way we respectively define and apply the distinction between the use and non-use benefits of research infrastructures, and of the measurable and non-measurable impacts, are also novel relative to the previous literature, as discussed in Florio and Sirtori (2015). Moreover, our treatment of risk, while based on standard Montecarlo methods, shows a way to forecast some stochastic variables typical of a CBA model

[28] The NPV would be lower if an opportunity cost of public funds is considered because of distortionary taxation, but it would still be positive for the typical current range in developed countries. In fact, European Commission (2014) does not recommend introducing a correction for the opportunity cost of public funds for projects funded by grants supported by international transfers, because it would not be clear which is the relevant source of funding. For example, if it is sovereign debt in Europe, for most of the core Member States of the CERN the real interest rate on such debt for 30 years bonds would be largely below the social discount rate that we use and below the long-term rate of growth of GDP. A sensitivity analysis can ascertain the relative impact of lowering the social discount rate and of increasing the total cost by a correction factor related to the opportunity cost of public funds, but we leave this and other sensitivity analysis issues for further research.

of large scale RI.

Clearly the LHC is a special, albeit important case of an RI, because of the long time of construction and operation, the high number of scientists, students and post-docs involved, the large number of firms in the supply chain, the externalities from the open access to software, the wide coverage in the media and the attraction of onsite visitors, and the nature of a frontier basic research facility. However, we believe that the role of a case study in social science is to suggest new avenues of inquiry. As stated by Flyvbjerg (2006 p.219):

"A scientific discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars, and that a discipline without exemplars is an ineffective one."

It would hence be necessary to expand further the evaluation of the socio-economic impact of RIs to other large-scale facilities, including those in applied science. An example of the latter is a recent study of the CNAO particle accelerator for hadron therapy (Pancotti et al. 2015), which uses, in the context of medical research, the same methodology we apply here. The proportion and scale of the costs and benefits may be different elsewhere, but we believe that the main ingredients of a CBA of research infrastructure are well represented in the LHC case; hence replication can be attempted if data are available. Further studies on a range of different facilities, in different science and technology domains, and in different countries, are needed to confirm our intuition.

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References

Abt, H.A. and E. Garfield. 2002. Is the Relationship between Numbers of References and Paper Lenghts the Same for All Sciences? Journal of the American Society for Information Science and Technology, 53**,** 1106-1112.

Arrow, K. J., and A.C. Fisher. 1974. Environmental Preservation, Uncertainty, and Irreversibility, Quarterly Journal of Economics, 88, 312-19.

Arrow, K., R. Solow, P.R. Portney, E.E. Leamer, R. Radner and Schuman, H. 1993. Report on the NOAA panel on contingent valuation. NOAA.

Atkinson, G. and S. Mourato. 2008. Environmental Cost-Benefit Analysis. Annual Review of Environment and Resources. 33, 317-344.

Autio, E., M. Bianchi-Streit and A.P Hameri A.P. 2003. Technology transfer and technological learn- ing through CERNs procurement activity. CERN-2003-005.

Bacchiocchi, E. and F. Montobbio, F. 2009. Knowledge diffusion from university and public re- search. A comparison between US, Japan and Europe using patent citations. Journal of Technology Transfer, 34, 169-18.

Bach L., G. Lambert, S. Ret, J. Shachar, with the collaboration of R. Risser, E. Zuscovitch, under the direction of P. Cohendet, M-J. Ledoux. 1988. Study of the economic effects of European space expenditure, ESA Contract No. 7062/87/F/RD/(SC).

Baum, W.C. and S.M. Tolbert. 1985. Investing in Development: Lessons of World Bank Experience Oxford: Oxford University Press.

Bezdek, R.H. and R.M. Wendling. 1992. Sharing out NASA's spoils. Nature, 355(6356), 105-106.

Bianchi-Streit, M., N. Blackburne, R. Budde, H. Reitz, B. Sagnell, H. Schmied and B. Schorr. 1984. Economic utility resulting from CERN contracts (second study), CERN, 84-14.

Boardman, A.E., D.H. Greenberg, A.R. Vining, and D.L. Weimer. 2006. Cost-Benefit Analysis: Concepts and Practice. Upper Saddle River NJ: Pearson Prentice Hall.

Boisot, M., M. Nordberg, S. Yami and B. Nicquevert (eds). 2011. Collisions and Collaboration. The Organization of Learning in the ATLAS experiment at the LHC. Oxford: Oxford University Press.

Brendle P., P. Cohendet, J.A. Heraud, R. Larue de Tournemine, H. Schmied. 1980. Les effets économiques induits de l' ESA. ESA Contracts Report Vol. 3.

Camporesi, T. 2001. High-energy physics as a career springboard, European Journal of Physics, 22, 2, 159-148.

Carrazza, S., A. Ferrara and S. Salini. 2014. Research infrastructures in the LHC era: a scientometric approach. Working Paper DEMM 2014-12, University of Milan.

Carson, R.T. 2012. 'Contingent Valuation: A Practical Alternative when Prices Aren't Available', Journal of Economic Perspectives, 26(4), 27-42.

Catalano G, C. Del Bo, M. Florio. 2015a. Human Capital Formation at LHC: Survey Results. http://wp.demm.unimi.it/tl_files/wp/2015/DEMM-2015_10wp.

Catalano G, Florio M., Giffoni F,. Forthcoming. Contingent valuation of social preference for science as a pure public good: the LHC case. DEMM Working paper, University of Milan.

CERN Communication Group. 2009. LHC the Guide FAQ. http://cds.cern.ch/record/1165534/files/CERN-Brochure-2009-003-Eng.pdf

Clawson, M. and J.L. Knetsch, J.L. 1966. Economics of outdoor recreation. Baltimore: Johns Hopkins Press.

Danish Agency for Science. 2008. Evaluation of Danish industrial activities in the European space agency (ESA). Assessment of the economic impacts of the Danish ESA membership. Technical report, Danish Agency for Science.

Drèze, J. and N. Stern. 1990. Policy reform, shadow prices and market prices. Journal of Public Economics 42, 1-45.

Drèze, J. and N. Stern. 1987. The theory of cost-benefit analysis. In A.J. Auerbach and M. Feldstein (eds), *Handbook of public economics*. Vol. 2, pp. 909-989. Amsterdam: North Holland.

Druckman, J N and C.D Kam, 2011 Students as experimental participants. A defense of the narrow data base, in James N. Druckman, Donald P. Green, James H. Kuklinsi, and Arthur Lupia eds, Cambridge Handbookof Experimental Political Science, New York: Cambridge University Press

DTZ. 2009. 'Economic impact of the John Innes Centre'. Technical report, DTZ, Edinburgh.

Eckhardt, R. 1987. Stan Ulam, John von Neumann, and the Monte Carlo method, Los Alamos Science 15, 131-137.

European Commission. 2014. Guide to Cost-Benefit Analysis of Investment projects. DG Regional and Urban Policy.

European Investment Bank. 2013. The Economic Appraisal of Investment projects at the EIB.

Feller, I., C.P. Ailes and J.D. Roessner. 2002. Impacts of research universities on technological innovation in industry: evidence from Engineering Research Centers. Research Policy, 31, pp.457-474.

Florio, M. 2014. Applied Welfare Economics: Cost-Benefit Analysis of Projects and Policies. New York: Routledge.

Florio, M. and E. Sirtori. 2015. Social Benefits and Costs of Large Scale Research Infrastructures, Technology Forecasting and Social Change, http://.doi/10.1016/j.techfore.2015.11.024

Florio, M., Forte, S., Pancotti, C., Sirtori, E., Vignetti, S. 2016. Exploring Cost-Benefit Analysis of Research, Development and Innovation Infrastructures: An Evaluation Framework. Working Papers, Centre for Industrial Studies (CSIL).

Flyvbjerg, B. Buzelius, N. Rothengatter, W. 2003. Megaprojects and Risk: An Anatomy of Ambition. Cambridge: Cambridge University Press.

Flyvberg, B. 2006. Five Misunderstandigs about Case-Study Research, Qualitative Inquiry, vol 12., n. 2, April pp 219-245.

Harmon, C. 2011. Economic returns to education:what we know, what we don't know, and where we are going. Some brief pointers, IZA Policy Paper n.29, August.

Myles, G.D. 1995. Public Economics. Cambridge, MA: Cambridge University Press

Hutton G. and G. Rehfuess. 2006. Guidelines for conducting cost-benefit analysis of household energy and health interventions. WHO Publishing.

Johansson, P.O. 1991. An Introduction to Modern Welfare Economics. Cambridge: Cambridge University Press.

Johansson, P.O. 1995. Cost-Benefit Analysis of Environmental Change. Cambridge: Cambridge University Press.

Johansson, P.O. and Kristrom B, 2015 Cost-Benefit Analysis for Project Appraisal, Cambridge: Cambridge University Press.

Knight, F. 1921. Risk, Uncertainty and Profit. 2nd edition 1964. Tallahassee, FL: Sentry Press.

Martin, B. R., and P. Tang. 2007. The benefits from Publicly Funded Research, SPRU Electronic Working Paper Series, Paper no. 161. University of Sussex, Brighton, UK: SPRU.

Montenegros C.E., Patrinos H.A. 2014, Comparable estimates of returns to schooling around the world, Policy Research Working paper 7020, September, Education Global Practice Group, World Bank Group

OECD. 2014. Report on the Impacts of Large Research Infrastructures on Economic Innovation and on Society. Case studies at CERN. Global Science Forum report. OECD Publishing, Paris.

OECD. 2015. Government at a glance. Paris: OECD.

Pancotti, C., G. Battistoni, M. Genco, M.A. Livraga, P. Mella, S. Rossi and S. Vignetti. 2015. The socio-economic impact of the National Hadron therapy Centre for Cancer Treatment (CNAO): applying a cost-benefit analysis analytical framework. DEMM Working Paper n. 2015-05.

Pearce, D.W., G. Atkinson, and S. Mourato. 2006. Cost-Benefit Analysis and the Environment: Recent Developments. Paris: OECD.

Pouliquen, L.Y. 1970. Risk Analysis in Project Appraisal, World Bank Staff Occasional Papers, 11. Baltimore: Johns Hopkins University Press.

Salina, G. 2006. Dalla ricerca di base al trasferimento tecnologico: impatto dell'attività scientifica dell'istituto nazionale di fisica nucleare sull'industria italiana, Rivista di cultura e politica scientifica, No. 2/2006.

Salling, K. B. and S. Leleur S. 2011. Transport Appraisal and Monte Carlo simulation by use of the CBA-DK model, Transport Policy, 18, 236-245.

Schmied, H. 1975. A study of economic utility resulting from CERN contracts. Technical report, European Organization for Nuclear Research, Geneva (Switzerland).

Schmied, H. 1982. 'Results of attempts to quantify the secondary economic effects generated by big research centers'. Engineering Management, IEEE Transactions on, EM-29(4):154-165.

Schopper, H. 2009. The Lord of the Collider Rings at CERN, 1980-2000. Heidelberg: Springer.

World Bank 2010, Cost-Benefit Analysis in World Bank projects, Fast Track Briefs, June 4 2010, World Bank, Washington DC