The potential socio-economic impact of a breakthrough in the particle accelerators’ technology

Massimo Florio
1. The research question
2. A general cost-benefit analysis model for research infrastructures
3. Two applications: LHC and CNAO
4. From a micro-economic to a meso-economic perspective
5. A research agenda
Our research question

How to evaluate the socio-economic impact of a technological breakthrough in particle accelerators?
By research in pure science. I mean research made without any idea of
application to industrial matters but solely with the view of extending our
knowledge of the Laws of Nature. I will give just one example of the
‘utility’ of this kind of research, one that has been brought into great
prominence by the War—I mean the use of X-rays in surgery...

“Now how was this method discovered? It was not
the result of a research in applied science to find an
improved method of locating bullet wounds. This
might have led to improved probes, but we cannot
imagine it leading to the discovery of the X-rays. No,
this method is due to an investigation in pure
science, made with the object of discovering what is
the nature of Electricity.”

J.J. Thomson (1911)
Our research question

The question can be made more explicit as follows:

“How can we predict and measure the benefits to different social stakeholders of a potential (uncertain) technological change that initially arises within a laboratory to solve scientific problems and then creates spillovers to technologies intended to solve socio-economic problems?“

- In an ex-post perspective the main problem is causality.
- In an ex-ante perspective the main problem is uncertainty about costs, time and effects of the change downstream, from the laboratory to the industries and public services.
History of CBA

FRANCE

“De la mesure de l'utilité des travaux publics”
(Annales des Ponts et Chaussées, 1844)

Jules Dupuit (1804 – 1866)
HISTORY OF CBA:

INTERNATIONAL ORGANISATION, USA AND UK

1936, Flood Control Act, US Government
1972, Guidelines for project evaluation, UNIDO
1974, Project appraisal and planning for developing countries by I.M.D. Little and J.A. Mirrlees, OECD
1975, Economic analysis of projects by L. Squire and H.G. van der Tak, World Bank
2013, EIB, The Economic Appraisal of Investment Projects at the EIB

1997: 2nd edition, 84 pages

2002: 4th edition, 133 pages


2014: 5th edition, 364 pages

A novelty of the fifth edition of EC CBA Guide:
Ch. 7 - Research, development and Innovation
Towards a CBA model for RIs

...A new CBA model
developed by the University of Milan
(DEMM and Dept. of Physics)
and CSIL

Cost-Benefit Analysis in the Research,
Development and Innovation Sector

Projects financed by EIBURS
the EIB University Research Sponsorship
Programme
Call for proposals
2012/C 162/10

December 2012 - December 2015
FINANCIAL

Financial Revenues - Financial Costs = Financial Profits

\[ \text{FNPV} = \sum_{t=0}^{T} \frac{p_t q_{ot} - p_t q_{it}}{(1+i)^t} \]

Financial Discount rate: 
\( i = 4\% \) for all EU Member States

ECONOMIC

Social Benefits - Social Costs = Social Net Benefits

\[ \text{ENPV} = \sum_{t=0}^{T} \frac{p^* t q_{ot} - p^* t q_{it}}{(1+r)^t} \]

Social Discount rate:
\( r = 5\% \) is used for major projects in Cohesion countries
\( r = 3\% \) for the other EU Member States

Market prices are unreliable or not existent for many RDI projects’ outputs.
The CBA model for RIs

\[ NPV_{RI} = NPV_u + B_n = (PV_{Bu} - PV_{Cu}) + B_n \]

- \( PV_{Bu} = \) present value of use-benefits
- \( B_n = \) non use-benefits
- \( PV_{Cu} = \) present value of costs

The expected economic net present value of the RIs infrastructure \([NPV_{RI}]\) over the time horizon \((T)\) is defined as the difference between expected benefits and costs valued at shadow prices and discounted at the social discount rate \((r)\).
Costs

\[ PV_{c_u} = \text{the present value of COSTS} \]

is the sum of

- economic value of capital \((K)\)
- labour cost of scientists \((L_S)\)
- other administrative and technical staff \((L_o)\)
- other operating costs \((O)\)
- negative externalities if any \((\varepsilon)\).

\[
\mathbb{E}(NPV_{c_u}) = \sum_{t=0}^{T} s_t \cdot (k_t + l_{st} + l_{ot} + O_t + \varepsilon_t)
\]

[2]

Discounting process is represented by \(T\) terms

\[ s_t = \frac{1}{(1+r)^t} \]
Benefits

FIRMS

Technological externalities ($T_i$)

EMPLOYEES: early career researchers

TAXPAYERS

Quasi option value (QOV) Existence value (EXV)

CONSUMERS

Social benefits to consumers of services ($A_i$)

SCIENTISTS

Knowledge output ($S_i$)

VISITORS

Cultural effects ($C_i$)

CONSUMERS

Non Use Benefits $B_n$

Quasi option value (QOV)

TAXPAYERS

Existence value (EXV)
Use Benefits

\[ PV_{B_u} = \text{the present value of use-benefits} \]

is the sum of

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

\[ \mathbb{E}(NPV_{B_u}) = \sum_{t=0}^{T} s_t \cdot (T_t + H_t + S_t + C_t + A_t) \] [3]
Benefits to firms: Technological spillovers

The present value of technological spillovers $T$ is given by the discounted incremental social profits $\Pi_{jt}$ by companies (j) of the RI’s supply chain or other economic agents, who have benefitted from a learning externality:

$$T = \sum_{j=1}^{J} \sum_{t=0}^{T} s_t \cdot \Pi_{jt} \quad [4]$$
Benefits to employees: Human capital formation

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

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

[5]
Benefits on users: knowledge output

The social value of knowledge output is measured by:

- the sum of the present value of papers signed by RDI's scientists ($P_{0t}$) and the value of subsequent flows of papers produced by other scientists that use or elaborate of the RDI’s scientists’ results

- divided by the number of references they contain ($\frac{P_{it}}{k_{it}}$, with $i = 1, ... n$), and the value of citations each paper receives, as a proxy of the social recognition that the scientific community acknowledges to the paper ($Q_{it}$ with $i = 0, ... n$)

\[
S = \sum_{i=1}^{n} \sum_{t=0}^{T} S_t \cdot P_{0t} + \sum_{i=1}^{n} \sum_{t=1}^{T} \frac{S_t \cdot P_{it}}{k_{it}} + \sum_{i=0}^{n} \sum_{t=1}^{T} S_t \cdot Q_{it} \tag{6}
\]

[6]
Benefits on users: cultural effects

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

\[
C = \sum_{g=1}^{G} \sum_{t=1}^{T} s_t \cdot W_{gt} \quad [7]
\]
Social benefits to consumers of services

Provision of Services

Some RDI infrastructures provide services to external users. They may pay a fee for accessing and using the infrastructure’s equipment and/or specific services offered.

Social benefits of RDI services for target groups of consumers

Some RDI infrastructures are expected to use new knowledge to deliver innovative services and products addressing specific societal needs. Benefits arise to users who are better off by the delivery of the innovative service or product.

\[ A = \sum_{a}^{A} \sum_{t=0}^{T} s_t \cdot a_t \]  

[8]

These services are project specific and each of them ultimately is related to the WTP for them by users.
Summing up:

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

\[
NPV_{RI} = \left[ \left( \sum_{j=1}^{J} \sum_{t=0}^{T} s_t \cdot \Pi_{jt} \right) + \left( \sum_{z=1}^{Z} \sum_{t=\varphi}^{T} s_t \cdot I_{zt} \right) + \left( \sum_{i=1}^{n} \sum_{t=1}^{T} \frac{s_t \cdot P_{it}}{k_{it}} \right) + \sum_{i=0}^{n} \sum_{t=1}^{T} s_t \cdot Q_{it} \right] \\
+ \left( \sum_{g=1}^{G} \sum_{t=1}^{T} s_t \cdot W_{gt} \right) + \left( \sum_{a=1}^{A} \sum_{t=0}^{T} s_t \cdot a_{t} \right) + (EXV_0) - \left[ \sum_{t=0}^{T} s_t \cdot (k_t + l_{ot} + o_t + \varepsilon_t) \right]
\]

If the **marginal cost of scientists’ labour input in publications is taken as a proxy of the value of knowledge outputs produced by scientists**, then \( l_{st} \) in equation (2) and \( P_{ot} \) in equation (6) **cancel each other** (under the reasonable assumption of linearity of the cost function).
CBA RESULTS (1)

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

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

2. The net present use-value of the research infrastructure is **equal to zero net of the unknown non-use effects**, $NPV_u = 0$;

3. The net present use-value of the research infrastructure is **negative net of the unknown non-use effects**, $NPV_u < 0$. 
CBA RESULTS (2)

• In the first two cases the RI passes the ex-ante CBA test if the evaluator guesses that the uncertain $B_n$ would be at least nil, so that the total $NPV_{RI}$ cannot be expected negative (within a range of associated probabilities). No further need to try to estimate $B_n$ as long as it can be excluded that non-use effects are non-negative.

• In the third case, which may be typical of fundamental research, the RI project passes the CBA test if and only if $B_n$ is positive and large enough to compensate for the negative net use-effects. An estimation of the willingness to pay for the pure value of discovery as a public good is needed.
The Large Hadron Collider: CBA results

PROBABILITY DISTRIBUTION OF THE LHC NET PRESENT VALUE

Own estimate of the Present Value PDF resulting from a Monte Carlo simulation (10,000 random extractions)

ESTIMATED PARAMETERS OF DISTRIBUTION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2,855,528</td>
</tr>
<tr>
<td>Median</td>
<td>2,825,860</td>
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<tr>
<td>Standard Deviation</td>
<td>2,134,763</td>
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<tr>
<td>Minimum</td>
<td>-6,220,259</td>
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<tr>
<td>Maximum</td>
<td>11,573,387</td>
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</table>

Estimated probabilities

<table>
<thead>
<tr>
<th>Event</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr. ENPV ≤ 0</td>
<td>0.086</td>
</tr>
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</table>

Values in Thousands EUR, 2013

Scientific publications 2%
Human capital formation 33%
Technological spillovers 32%
Cultural effects 13%
Existence value 20%
CNAO - Hadron Therapy: CBA results

**PROBABILITY DISTRIBUTION OF THE CNAO NET PRESENT VALUE**
Own estimate of the Present Value PDF resulting from a Monte Carlo simulation (10,000 random extractions)

- Carbon Ion Therapy 74.2%
- Proton Therapy 20.9%
- Revenues 2.2%
- Benefit of Technological Spillovers 1.1%
- Benefit of Human Capital Generation 0.7%
- Benefit of Knowledge Creation 0.6%
- Benefit of Cultural Outreach 0.3%

**VALUES IN THOUSANDS EUR, 2013**

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<td><strong>Minimum</strong></td>
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<td><strong>Maximum</strong></td>
<td>3,686,989</td>
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Estimated probabilities
- **Pr. ENPV ≤ 0** 0.000

Values in Thousands EUR, 2013

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ENPV Probability Density Function

ENPV Cumulative Distribution Function
We are not willing to evaluate a single research infrastructure but a breakthrough that can have an impact on several uses of particle accelerators.

One can start by a partial equilibrium perspective
Net benefits of a cost saving technological change
There are some **200 high-and medium energy machines** and probably as many as **16,000 smaller accelerators**.

- **200** are to produce radioisotopes for medicine; almost **8,000** are employed in the therapy of cancer, and another **8,000** for industrial processing, ion implantation, modification of surface and bulk materials and for sterilization of food....
10,000 cancer patients daily treated in the US with beams from accelerators.

10 million diagnostic medical procedures and 100 million laboratory tests every year with short-lived radioisotopes.

$20 billion business annually of nuclear diagnostic medicine and radiation therapy.

The multi-billion-dollar semiconductor industry relies on ion beams from accelerators to add special atoms in semiconductors.

X-ray lithography with intense beams etches microchips and other semiconductor devices.

Nondestructive dating of archeological samples and art objects, for unraveling DNA structure, and for pharmaceutical research.
“Any charged particle accelerator that generates an external electron or ion beam for any beam process other than direct medical treatment or basic research to be an industrial accelerator. We do not include self-contained low-energy devices such as cathode ray tubes, X-ray tubes, radio frequency and microwave power tubes, and electron microscopes in this category even though they are used mostly for industrial purposes. However, we do consider the accelerator production of therapeutic or diagnostic radionuclides for nuclear medicine an industrial application because these are either stand-alone ingredients or end products that are for the most part produced by for-profit businesses using commercially-built accelerators”.

More than 24,000 particle accelerators over the past 60 years for use in the industrial processes. More than 11,000 particle accelerators exclusively for medical therapy with electrons, ions, neutrons, or X-rays.
Industrial applications: (2)
Hamm and Hamm (2012)

- Useful lifespan of 20 to 40 years and more than 75% of those built are still in operation today.
- At least 70 companies and institutes around the world.
- A few large vendors in North America, Europe, and Japan, but the number of vendors in Russia, India, Korea, and China is growing rapidly.
- H&H estimate that collectively these accelerator manufacturers ship more than 1100 industrial systems per year — almost twice the number produced for research or medical therapy — at a market value of ~US 2.2B.
- The annual sales of ion implanter accelerators alone is greater than US 1B and the market value of semiconductor devices produced is approaching US 300B worldwide.
A taxonomy of benefits in RIs

Customary partition of economic agents in the applied welfare economics literature:

- **Firms**: profit maximization (producer surplus).
- **Consumers**: maximizing their utility (consumer surplus).
- **Employees**: maximizing their income for a given amount of efforts.
- **Tax-payers**: adjusting their decisions as a consequence of the existing fiscal constraints to minimize the burden of taxation.

Some evidence from literature:
A future agenda of a research on the Socio-economic impact of a breakthrough in accelerator technology should include:

- **Adapting a social cost-benefit analysis of research infrastructures** to the specific topic of an entirely new concept: a) A long-term forecast of the global demand for particle accelerators; b) probability of discovery and scenario analysis of the technological change; c) assessment of the potential socio-economic net benefit of the transition to new technologies.

- **Review of the existing information on the global stock and demand of particle accelerators.** The estimate of more than 30,000 accelerators is often reported but not very precise and updated: *in which application fields there will be the greater impact?* It would be needed to estimate the existing stock and demand drivers of the accelerators worldwide in the different sectors, and second to focus particularly on those accelerators which are potentially of specific interest for a technological change if and when new types of accelerators will be available in future.
Given the uncertainty surrounding the field, a specific technology forecasting exercise, based on state-of-the-art approaches (following Delphi approach) should be performed, involving an international panel of scientists and experts in the R&D of acceleration industry. The specific objective is to generate a subjective (Bayesian) probability distribution of different technological scenarios, conditional to existing information.

Combining the demand scenario for particle accelerators of the type potentially influenced by a technological breakthrough, and the R&D scenario, the cost-benefit analysis will be based on the simple concept that the main potential net socio-economic benefit is driven by the difference between the cost trajectory of the current technologies and the cost trajectory of the new technologies.
A research agenda (3)

- Other benefits may include the effects on human capital (PhD students), technological spillovers, cultural effects. These concepts will be captured quantitatively by the expected net present value (NPV) of such difference, over a suitable long-term intertemporal integration, given a social discount rate (currently the EC recommend 0.03 in real terms).

- Given the high uncertainty surrounding both the demand drivers and the cost savings, several variables in the forecasting model will be treated as stochastic and the final result will be expressed in the form of a conditional probability distribution of the NPV after a suitable Montecarlo exercise.
Suggested Readings


- Special Issue on The social impact of Research Infrastructures at the frontiers of science and technology. 2016. Guest editors: Chiara Del Bo, Massimo Florio and Stefano Forte.


THANK YOU
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