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DIPARTIMENTO DI ECONOMIA

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ISSN 2279-6916 Working papers
(Dipartimento di Economia Università degli studi Roma Tre) (online)

Working Paper n° 225, 2017

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Big Science, Learning and Innovation: Evidence from CERN Procurement[1]

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Abstract

We study the way in which public procurement by big research infrastructures enhances suppliers' performance. Using survey data on 669 CERN suppliers, we built a unique data set to analyse, through an ordered logit model and Bayesian networks, the determinants of suppliers' sales, profits and development activities. We find that collaborative relations between CERN and its suppliers improve suppliers' performance and increase positive spill overs along the supply chain. This suggests that public procurement for innovation policies should promote cooperative relations and not only market mechanisms.

JEL classification: O310, O330, O380, C110

Keywords: Big Science, Public Procurement, CERN, Suppliers

Acknowledgements: The authors are very grateful for their support and advice to the following experts at CERN: Frédérick Bordry, Johannes Gutleber, Lucio Rossi, Florian Sonneman, and Anders Unnervik. The contribution of Isabel Bejar Alonso and Celine Cardot from CERN procurement department in providing and interpreting the procurement data as well as financial support from the Rossi-Doria Centre are gratefully acknowledged.
Helpful assistance with data collection was also provided by Efrat Tal Hod. A special thanks goes to Gelsomina Catalano (University of Milan) for having managed the contacts with the companies surveyed, and having administered the on-line survey.
We are also grateful for their comments on an earlier version to Stefano Forte (University of Milan) and Francesco Crespi (Roma Tre University) and to participants at the workshop "The economic impact of CERN colliders: technological spillovers, from LHC to HL-LHC and beyond" held in Berlin in May 2017 during the Future Circular Collider Week.
This paper should not be reported as representing the official views of the CERN, or any third party. Any errors remain those of the authors.

1 Introduction

We are interested in studying the mechanisms through which technological procurement by government-funded science organisations can have an impact on learning, innovation and, ultimately, performance in their supplier firms.

Inquiry into these mechanisms is important for several reasons. Policy makers and scholars are increasingly emphasizing the role of public procurement as a demand-driven tool for stimulating and promoting innovation (Lember at al., 2015; Knutsson and Tomasson, 2014; Aschhoff and Sofka, 2009, Martin and Tang, 2007). Public procurement for innovation (PPI) is meant to stimulate innovation by shaping the demand environment and the economic landscape in which suppliers operate (Uyarra and Flanagan, 2010). In fact, contracts with procuring organisations that require the development of non-routine technologies are likely to cause radical changes in suppliers' activities, challenging them to supply cutting-edge products (Salter and Martin, 2001; Perrow, 1967). In such a context, the firm may need to adjust organisational structure and production, and develop technological solutions to meet the public procurer's request. PPI is thus likely to lead to radical innovations and lay the foundations for new markets, particularly in areas where market interest is suboptimal owing to high risk and uncertainty (Mazzucato, 2016; Lember et al., 2015).

But how exactly does PPI affect a firm's performance? The evidence concerning its effectiveness is largely anecdotal, lacking a clear theoretical and empirical basis for understanding how public procurers actually influence firms' innovation capabilities and performance and the channels through which this creates spillovers in the market (Åberg and Bengtson, 2015; Georghiou et al., 2014).

This paper aims to fill that gap. We address the basis of the innovation procurement process by inquiring into what works and how. Our focus is on the mechanisms that explain how public procurers can support learning and innovation in their industrial partners, and how these buyer-supplier relationships influence the latter's performance.

In this paper we propose a conceptual framework rooted in the PPI literature on interaction modes between economic actors (i.e. public buyers and private suppliers) as fundamental drivers of innovation and firms' potential success (Sorenson, 2017; Edquist et al., 2015; Edquist and Zubala-Iturriagagoitia, 2012; Williamson, 2008; Paulraj et al., 2008; Swink et al., 2007; Lundvall, 1985; Rothwell, 1984). The literature on the procurement of science organisations that operate large-scale research infrastructures (RIs)[2] offers interesting insights on the way in which such centres act as risk takers, reducing suppliers' perceived risk in undertaking projects at the frontier of science (Unnervik, 2009); it underlines industrial knowledge spillovers generated in the economy through their procurement activity (Nilsen and Anelli, 2016; Autio et al., 2004; Bianchi-Streit et al., 1984; Schmied, 1977). Industrial suppliers benefit from demand-side learning and interactions with the research organisations, which in turn can strengthen their own performance. The benefits acquired by first-tier suppliers can then be transferred onward to other companies that are part of the supply network (Science|Business, 2015; Nordberg et al., 2003).

The testing ground for our study is the European Organisation for Nuclear Research (CERN), the world's leading laboratory for experimental particle physics. For our purposes, CERN offers an ideal case study. Its mission is not only to study the basic constituents of matter, but also to advance the frontier of technology and maximise the impact of the science, technology and know-how that it produces on industry and the society as a whole (Lebrun and Taylor, 2017). Many technologies developed for CERN have found applications in other sectors – from aerospace to medicine – and have addressed societal challenges in health, energy, environment and other fields (Amaldi, 2012). CERN is a "learning environment" for industrial supplier companies. Autio (2014) and Bianchi-Streit et al. (1984) show the Organisation's impact on suppliers' capacity to develop new products, generate organisational innovation, and acquire technological and market learning.

To answer our research questions, in 2017 we conducted an online survey addressed to CERN suppliers, building a unique data base on the types of goods and services delivered by each firm, the type of relationship established with CERN, the variety of learning and performance benefits enjoyed, and the benefits to second-tier suppliers.

Initially we test a set of research hypotheses with an ordered logit model to investigate the correlations of CERN suppliers' performance (sales, profits, and development activities) with determinants suggested by the PPI literature. Then we use Bayesian Network analysis (BN) (Ben-Gal, 2007; Pearl, 2000), for a more in-depth examination of the interlinks between the variables that explain suppliers' performance.

We contribute to the literature on PPI from at least three standpoints. First, we offer a work on an under-researched area in the economic literature on the impact of PPI at firm level, by disentangling some of the channels through which this effect may be produced and pointing out some interactions among them.

Second, we innovate methodologically both by constructing new indicators and by showing that multiple causal linkages between the procurement relations are better captured by combining BNs as a complement to standard econometric models, in line with the idea that the proper evaluation of public investments and their results "requires new methods, metrics and indicators" (Mazzucato, 2015: 9).

Third, we put "some more meat on the bones" of the question of governance structure. To the best of our knowledge, this is the only paper that accords proper importance to the different governance structures and to their differential impact on suppliers' performance in a context of risky, uncertain, innovative and transaction–specific investments.

We attain three main results.

1) In line with the predictions of transaction cost theory, recently revived by the Global Value Chains literature (Gereffi et al., 2005), our findings indicate that CERN's procurement has a significant impact on suppliers' performance when cooperative relations are in place, and a more modest impact in the case of arm's length market relations.

2) The benefits of Big Science procurement spill over to second-tier suppliers, creating more widespread impact on firms across the entire innovation supply chain.

3) The heterogeneity of firms does matter. The impact on the suppliers' performance depends critically on their absorptive capacity.

The rest of the paper proceeds as follows. Section 2 presents the conceptual model and our research hypotheses. Section 3 describes the research design, the descriptive statistics of the survey responses and the statistical approaches to processing them. The results are presented in Section 4. Section 5 concludes with a discussion of policy implications, caveats and suggestions for future research.

2 The conceptual framework: theoretical foundations and research hypotheses

Innovation is a complex process that takes time and is influenced by multiple factors (Håkansson et al., 2009; Phillips et al., 2006; Dosi et al., 1988). This complexity induces firms to interact with other organisations for knowledge exchange and technological learning, so that interactive learning becomes a fundamental driver of innovation (Cano-Kollmann et al., 2017; Edquist, 2011; Rothwell, 1994; Lundvall, 1993 and 1985). Chesbrough (2003) defines open innovation as an intentional exchange of inflows and outflows of knowledge between a firm and external parties to accelerate the firm's internal innovation. Von Hippel (1986) observes that the users and suppliers were sometimes more important as functional sources of innovation than the product manufacturers themselves. Emphasising the need for communication with the user side of innovations, Von Hippel introduced the term "lead-users", defined as "users whose present strong needs will become general in a market place months or years in the future" (von Hippel, 1986: 791).

This line of argument implies not only that the development and diffusion of innovations through PPI depend on user-producer interaction in the procurement process (Newcombe, 1999; Mowery and Rosenberg, 1979), but also that science organisations, such as CERN, can be seen as "lead-users" acting as learning environments for suppliers, who often strive to meet the stringent technological specifications of the projects planned (Unnervik, 2009). Autio et al. (2004) argue that communication and interaction in the dyad consisting of big science and industry mainly take the form of technological learning by the latter from the former.

2.1 Relationships and governance structures

The most common way in which PPI has been seen as influencing innovation has been as a channel for the flow of information and interactions among economic actors (Georghiou et al., 2014; Edquist and Zubala-Iturriagagoitia, 2012; Nordberg at al., 2003). The neo-institutional theory of the firm sees procurement as a form of outsourcing in a context of incomplete contracts aimed at minimising transaction costs (Williamson, 2008 and 1975; Grossman and Hart, 1986; Coase, 1937). The extent of the interchange of knowledge among companies varies considerably according to their mode of participation in the supply network and depends on the type of relations that they entertain with other firms. The firms' own way of operating within the network is then embedded in the notion of governance structures of the supply network (Williamson, 1991), which determines bilateral dependency among the members of a supply network, the degree to which they interact and cooperate, and hence the possibility of mutual learning.

Williamson (2008: 10) indicates that the heterogeneous set of buyer-supplier relationships can be simplified into five main governance structures, i.e. *markets, credible (or modular), benign (or relational), muscular (or captive),* and *hierarchy*[3]*:* as bilateral dependency is built up through transaction–specific investments, the efficient governance of contractual relations moves from simple market exchange to hybrid contracting (e.g. modular, captive), then to relational and finally to hierarchy (Williamson, 2008) to eliminate the risk of agents' opportunistic behaviour. The hierarchical structure is characterised by vertical integration and fully in-house production. In the context of our study, we focus on the relationship between CERN and its supplier firms, and between these suppliers and other firms as subcontractors. That is, we leave aside the hierarchical mode of governance and focus on the others. In particular, we distinguish between market governance, relational governance and hybrid governance.

- *Market governance* involves simple transactions that are not difficult to codify in contracts and where the central governance mechanism is price. Such transactions require little or no formal cooperation or dependency actors.
- *Relational governance* implies that buyer and supplier cooperate regularly to deal with complex information that is not easily transmitted or learned. This produces frequent interactions and knowledge-sharing in order to remedy the incompleteness of contracts and deal flexibly with all possible contingencies. Relational governance consists of linkages that take time to build and that generate mutual reliance, so the costs and difficulties of switching to a new partner tend to be high.
- *Hybrid forms of governance* comprise modular and captive governance forms. Both are hybrid forms lying somewhere between market and relational governance, in which transactions may incorporate some degree of cooperation and knowledge exchange between the parties, depending on the complexity of the information to be exchanged. In this case linkages between the public procurer and suppliers are more substantial than in simple markets, but less than in relational governance.

Our hypothesis is that, in the context of large-scale RI procurement, these systems of governance between science organisations and supplier firms are shaped by the level of innovation in procurement orders and the money volume of the orders received by the suppliers. The level of innovation is a multifaceted construct, related to the notions of technological novelty and technological uncertainty. Technological novelty refers to the product's newness with respect to the supplying firms' competencies and to the worldwide state of the art. The level is a crucial element in relationship outcomes – it is expected to be positively associated with learning potential (Autio, 2014; Autio et al., 2004; Schmied, 1977 and 1987). Technological uncertainty refers to the likelihood of the products' specifications being achieved. Both novelty and uncertainty play key roles in the willingness of parties to share knowledge and are expected to impact positively on the innovation capabilities of suppliers. In the case of CERN, for instance, the laboratory has often helped firms to develop new product lines by testing prototypes. This approach has both reduced the uncertainty surrounding the order (Unnervik, 2009) and provided an initial impetus to the firm's innovation capability. The size of the order (or the sum of the value of orders received by the same company) is also expected to shape the interaction modes between science public organisations and industrial suppliers. This leads to our first research hypothesis:

Hypothesis 1. The level of innovation and the value of orders shape the relationship between CERN and its suppliers. Specifically, the larger and the more innovative the order, the more likely the CERN and its suppliers are to establish relational governance, as a remedy for contract incompleteness, agents' opportunism, and suboptimal investments on both sides.

2.2 Learning, innovation and market outcomes

Potential outcomes accruing to suppliers from their relationships with science organizations are likely to vary considerably according to the governance structures. Following Autio et al. (2004) and Bianchi-Streit et al. (1984), we distinguish three categories of cooperation outcomes.

Innovation outcomes. These relate to the development of new products, services and technologies, and changes in the technological status of the suppliers (e.g. the acquisition of patents or other forms of intellectual property rights, or IPR).

Learning outcomes. These relate to the acquisition of technical know-how, improvement in the quality of products and services, changes in production processes, organisational and management activities initiated thanks to the supply relationships.

Market penetration outcomes. These include both the direct acquisition of new customers and market benefits in terms of improved reputation as the big-science centre acts as a marketing reference for the company.

The achievement of one or more of these outcomes by suppliers depends on the governance structure that shapes the RI-company dyad. For instance, high technological novelty and transaction-specific investments characterise highly structured types of governance (i.e. relational). Thus, we expect innovation outcomes to be associated with tighter inter-firm linkages.

By contrast, market-related outcomes are likely to accrue also to those companies that establish a less structured relationship with the science organisation. In fact, Autio et al. (2004) and Bianchi-Streit et al. (1984) document that reputational benefits are likely to accrue simply from becoming the supplier of a world-renowned laboratory like CERN. In that case, the science organisation is exploited by the firms as a signal for other potential customers in the market. These leads to our second research hypothesis:

Hypothesis 2. The relational governance of procurement is positively related to innovation and learning outcomes for the suppliers of large-scale science centres.

2.3 Supplier's performance

Governance structures are instrumental to innovation, learning and market outcomes. These outcomes, which we call "intermediate", impact in turn on suppliers' performance (Autio et al., 2004; Bianchi-Streit et al., 1984). In order to investigate this specific aspect, we look at different performance variables: sales, profit dynamics, and business development (i.e. establishing a new R&D unit, starting a new business unit, entering a new market).

Nordberg et al. (2003) and Bianchi-Streit et al. (1984) provide evidence that the rigorous technical requirements of large-scale RIs may lead firms to make significant changes in their production processes and activities, which may have adverse effects on their performance, in some extreme cases even resulting in bankruptcy. However, we argue that the effects of learning, innovation and market penetration on economic performance (sales and/or profits) and development activities are expected to be generally positive. This is reflected in our third research hypothesis.

Hypothesis 3. Innovation, learning and market penetration by the large-scale science centres' suppliers are likely to impact positively on their performance.

2.4 Governance structures and outcomes in second-tier suppliers

A few studies have shown that innovation and knowledge diffusion in the RI-industry dyad is not limited to first-tier suppliers but can spread throughout the entire supply network (Autio et al., 2004; Nordberg et al., 2003). As in the case of first-tier suppliers, the extent to which second-tier suppliers benefit from innovation, learning and market outcomes depends heavily on the governance structures they establish with the first-tier suppliers. We look at the outcomes for second-tier suppliers, such as increased technical know-how, product and process innovation, as well as market outcomes. Thus, we formulate the following hypothesis:

Hypothesis 4. In the case of relational governance of procurement, the innovation, learning and market outcomes are not confined solely to first-tier suppliers but spread to second-tier suppliers as well.

Our research hypotheses finalise our conceptual model, which is shown in Figure 1.

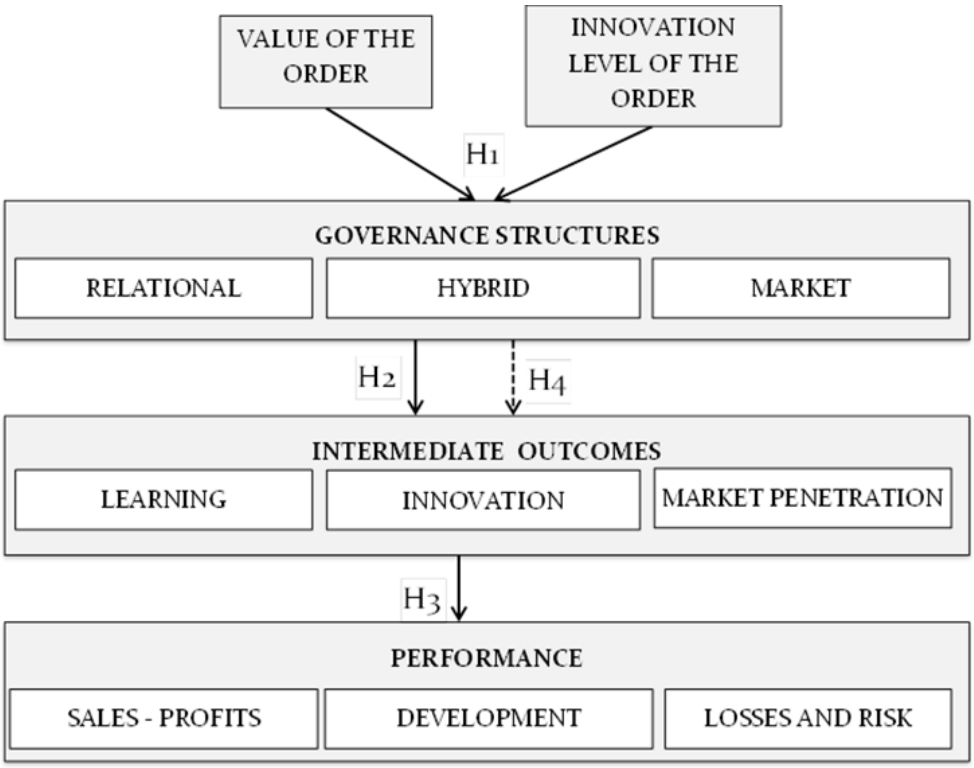

Figure 1. Conceptual Model

3 Research design, descriptive statistics and methods

3.1 The survey

In order to test our hypotheses, we developed a broad on-line survey addressed to CERN's supplier companies, conducted between February and July 2017. CERN granted us access to its procurement database, producing a list of the suppliers that received at least one order larger than EUR 6,100[4] between 1995 and 2015. The database counts some 4,200 suppliers from 47 countries and a total of about 33,500 orders for EUR 3 billion. About 60% of the firms (2,500) had a valid e-mail contact at the time of the survey.

Following our conceptual model, we structured the on-line questionnaire in three sections, bearing respectively on: *i)* the relationship between the respondent supplier and CERN, *ii)* the impact of CERN's procurement on the supplier' performance as perceived by the supplier, and *iii)* the relationship between the firm and its subcontractors. We used both closed-ended questions and five-point Likert scale questions to enable companies to say how much they agreed or disagreed with every statement.

Respondents numbered 669, or 25% of the target population (i.e. companies with an e-mail contact). This response rate can be considered satisfactory for this kind of survey and is of comparable size to similar previous surveys (Autio et al., 2003; Bianchi-Streit et al., 1984).

3.2 Descriptive statistics

The survey produced responses from 669 suppliers in 33 countries, mainly from Switzerland (27%), France (20%), Germany (14%), Italy (8%), the UK (7%), and Spain (5%).

Respondent firms are mainly medium-sized and small companies (43% and 26% respectively). Large companies made up 23% of the sample and very large companies the remaining 8%.[5] On average, each supplier processed 12 orders (standard deviation = 36) and received EUR 63,000 per order (standard deviation = EUR 126,000). Before becoming a CERN supplier, 45% of the respondents stated that they had had previous experience in working with large laboratories such as CERN.

The sample includes firms that supplied a highly diversified range of products and services to CERN, from off-the-shelf and standard commercial products to highly innovative, cutting-edge products and services (Table 1).

In the delivery of the procurement order, 52% received some additional inputs from CERN staff, besides the order specifications, and 20% engaged in frequent cooperation with CERN (Table 2).

Table 1. Innovation level of products delivered to CERN[6]

Innovation level of products and services	N
Products and services with significant customisation or requiring technological development	331
Mostly off-the-shelf products and services with some customisation	239
Advanced commercial off-the-shelf or advanced standard products and services	172
Cutting-edge products /services requiring R&D or co-design involving the CERN staff	158
Commercial off-the-shelf and standard products and/or services	110

Table 2. Governance structure

Governance structure	N	%
During the relationship with CERN, we carried out the project(s) on the basis of …		
the specifications provided, but with additional inputs (clarifications, cooperation on some activities) from CERN staff	349	52%
the specifications provided with full autonomy and little interaction with CERN staff	181	28%
frequent and intense interactions with CERN staff	133	20%

To examine the relationship between CERN and its suppliers more closely, we asked about specific aspects of their mode of interaction (Table 3).

Table 3. Specific aspects of the supply relationship. Scale: 1 = strongly disagree; 5 = strongly agree.

Question	N	Mean	% of suppliers that agree or strongly agree
During the relationship with CERN …			
We were given access to CERN laboratories and facilities	668	3.18	43%
We always knew whom to contact in CERN to obtain additional information	669	4.24	86%
We always understood what CERN staff required us to deliver	669	4.21	87%
CERN staff always understood what we communicated to them	669	4.19	87%
During unexpected situations, CERN and our company dialogued to reach a solution without insisting on contractual clauses	668	3.91	68%

Suppliers were asked about the impact that the procurement relationship with CERN had on their company (Table 4). In terms of learning outcomes, 55% said that thanks to the relationship, they had increased their technical know-how; 48% reported that they had improved products and services. Innovative outcomes were achieved as a result of new knowledge acquired; 282 firms stated they had managed to develop new products, and new services or new technologies were introduced by 203 and 138 suppliers respectively.[7]

The responses on market penetration outcomes reveal that 62% of firms used CERN as a marketing reference and declared that they had improved their reputation as suppliers. Around 20% of the firms said they had gained new customers of different types.

In line with our hypotheses, we expected an improvement of suppliers' performance thanks to the work carried out for CERN. And in fact 18% of firms reported that they had increased sales in other markets (i.e. apart from sales to CERN). Most of firms interviewed experienced no financial loss and did not face risk of bankruptcy as a consequence of CERN procurement.

Table 4. Innovation outcomes and economic performance. Scale: 1 = strongly disagree; 5 = strongly agree.

Question	N	Mean	% of suppliers that agree or strongly agree
Learning outcomes			
Thanks to CERN, supplier firms			
Acquired new knowledge about market needs and trends	668	3.19	35%
Improved technical know-how	668	3.54	55%
Improved the quality of products and services	669	3.41	48%
Improved production processes	669	3.14	31%
Improved R&D production capabilities	669	3.19	34%
Improved management/organisational capabilities	669	3.12	28%
Innovation outcomes			
Because of the work with CERN, supplier firms developed:			
New products	282		
New Services	203		
New technologies	138		
New patents, copyrights or other IPR	22		
None of the above	65		
Market penetration			
Because of the work with CERN, supplier firms ...			
Used CERN as important marketing reference	669	3.61	62%
Improved credibility as supplier	669	3.68	62%
Acquired new customers - firms in own country	669	2.73	23%
Acquired new customers - firms in other countries	666	2.69	23%
Acquired new customers - research centres and facilities like CERN	668	2.66	24%
Acquired new customers - other large-scale research centres	669	2.49	14%
Acquired new customers - smaller research institutes/universities	669	2.71	22%
Performance			
Because of the work with CERN, supplier firms ...			
Increased total sales (excluding CERN)	669	2.63	18%
Reduced production costs	669	2.30	3%
Increased overall profitability	668	2.51	12%
Established a new R&D team/unit	669	2.22	6%
Started a new business unit	669	2.14	6%
Entered a new market	669	2.46	16%
Experienced some financial loss	669	2.04	7%
Faced risk of bankruptcy	339	1.56	1%

Table 5 and Table 6 report responses related to the relationship between the respondent firms (first-tier suppliers) and their subcontractors (second-tier suppliers), focusing on the type of benefits accruing to the latter.

More specifically, firms were asked whether they had mobilised any subcontractor to carry out the CERN project(s), and if so to list the number of subcontractors and their countries as well as the way in which the subcontractors were selected. In all, 256 firms (38%) mobilised about 500 subcontractors (averaging 2 per firm) in 26 countries. Good reputation, trust developed during previous projects, and geographic proximity were the most commonly reported means of selection of these partners. The remaining 413 firms (62%) did not mobilise any subcontractor, mainly because they already had the necessary competencies in-house.

The types of product provided by subcontractors to the firms interviewed are listed in Table 5 under the label "Innovation level of products and services". For instance, 80 firms (31%) declared that their subcontractors supplied them with mostly off-the-shelf products and services with some customisation; only 3% said that they had supplied cutting-edge products and services.

Table 5. Innovation level of products and governance structure within the second-tier relationship.

Innovation level of products and services	**N**	**%**
Mostly off-the-shelf products and services with some customisation	80	31%
Significant customisation or requiring technological development	44	20%
Advanced commercial off-the-shelf or advanced standard products and services	40	16%
Commercial off-the-shelf and standard products and/or services	32	13%
Cutting-edge products /services requiring R&D or co-design involving the CERN staff	8	3%
Mix of the above	52	20%
Total	**256**	**100%**
Governance structure		
Our subcontractors processed the order(s) on the basis of …		
our specifications, but with additional inputs (clarifications, cooperation on some activities) from our company	119	46%
our specifications with full autonomy and little interaction with our company	87	34%
frequent and intense interactions with our company	50	20%
Total	**256**	**100%**

As regards the governance structure between first-tier and second-tier suppliers, 46% of the firms gave their subcontractors additional inputs beyond the basic specifications, such as clarifications or cooperation on some activities; 34% said that the subcontractors operated with full autonomy, while 20% established frequent and intense interactions with their subcontractors.

Table 6. Benefits for second-tier suppliers as perceived by first-tier suppliers.

Question	N	Mean	% of suppliers that agree or strongly agree
To what extent do you think that your subcontractors benefitted from working with your company on CERN project(s)? Our subcontractors …			
Increased technical know-how	256	3.14	37%
Innovated products or processes	256	2.91	23%
Improved production process	256	2.89	18%
Attracted new customers	256	2.89	21%

According to the perception of respectively 37% and 23% of the supplier firms, subcontractors may have increased their technical know-how or innovated their own products and services, thanks to the work carried out in relation to the CERN order (Table 6).

3.3 The Empirical Investigation

The data were processed by two different approaches. The first was standard ordered logistic models, with suppliers' performance, variously measured, as the dependent variable. The aim is to determine correlations between suppliers' performance and some of the possible determinants suggested by the PPI literature. Second was a Bayesian Network (BN) analysis to study more thoroughly the mechanisms within the science organisation or RI-industry dyad that could potentially lead to a better performance of suppliers.

BNs are probabilistic graphical models that estimate a joint probability distribution over a set of random variables entering in a network (Salini and Kenett, 2009; Ben-Gal, 2007) BNs are increasingly gaining currency in the socio-economic disciplines (Florio et al., 2017; Sirtori et al., 2017; Cugnata et al., 2017; Ruiz-Ruano Garcia et al., 2014). By estimating the conditional probabilistic distribution among variables and arranging them in a Directed Acyclic Graph (DAG), BNs are both mathematically rigorous and intuitively understandable. They enable an effective representation of the whole set of interdependencies among the random variables without distinguishing dependent and independent ones. If target variables are selected, BNs are suitable to explore the chain of mechanisms by which effects are generated (in our case, CERN suppliers' performance) producing results that can significantly enrich the ordered logit models (Pearl, 2000).

3.4 Variables

We pre-treated the survey responses in order to obtain the variables that were entered into the statistical analysis, in line with our conceptual framework (see the full list in Table 7). The type of procurement order was characterised by the following variables:

- *High-tech supplier* is a binary variable, taking the value of 1 for high-tech suppliers, i.e. those companies that in the survey reported having supplied CERN with products and services with significant customisation or requiring technological development, or cutting-edge products/services requiring R&D or co-design involving the CERN staff.
- *Second-tier high-tech supplier.* We apply the same methodology as for the first-tier suppliers.
- *EUR per order* is the average value (in euro) of the orders the supplier company received from CERN. This continuous variable was discretised to be used in the BN analysis. It takes the value 1 if it is above the mean (EUR 63, 000) and 0 otherwise.

Two types of variable were constructed in order to measure the governance structures. One is a set of binary variables distinguishing between the *Market*, *Hybrid* and *Relational* modes of interaction. The second is a more complex construct that we call *Governance.*

- *Market* is a binary variable taking the value 1 if suppliers processed CERN orders with full autonomy and little interaction with CERN, and 0 otherwise. The same codification was used for the second-tier relationship (*Second-tier market*).
- *Hybrid* is a binary variable taking the value 1 if suppliers processed CERN orders on the basis of specifications provided but with additional inputs (clarifications, cooperation on some activities) from CERN staff and 0 otherwise. The same codification was used in the second-tier relationship (*Second-tier hybrid*).
- *Relational* is a binary variable taking the value 1 if suppliers processed CERN orders with frequent and intense interaction with CERN staff and 0 otherwise. The same codification was used in the second-tier relationship (*Second-tier relational*).
- *Governance* was constructed by combining the five items reported in Table 3. Each was transformed into a binary variable by assigning the value of 1 if the respondent firm agreed or strongly agreed with the statement and 0 otherwise. Then, following Cano-Kollmann et al. (2017), the

Governance variable was obtained as the sum of the five binary items (its value accordingly ranging from 0 to 5). We test the internal reliability of this variable by using Cronbach's Alpha, which worked out to 0.74, hence above the commonly accepted threshold value of 0.7 (Tavolok and Dennick, 2011), indicating a high degree of internal reliability that the items examined actually are measuring the same underlying concepts. Thus, the higher the value of this variable, the more the interaction mode between suppliers and CERN approximates a relational-type governance structure.

Intermediate outcomes are captured by the following variables (Table 4):

- *Learning.* Each of the six items in this category of outcomes was transformed into a binary variable, and then combined into a variable obtained as the sum of the six binary items, ranging in value from 0 to 6 (Alpha = 0.90.)
- *Innovation.* This was measured by four binary variables taking the value 1 if the respondent ticked the corresponding option (new products, new services, new technologies, new patents or other IPR) and 0 otherwise.
- *Market penetration* is measured by two variables.
  - *Market reference,* defined as the sum of two binary items, hence ranging in value from 0 to 2 (Alpha = 0.78). The items were: "used CERN as an important marketing reference" and "improved credibility as a supplier".
  - *New customers*. Like learning outcomes, this variable was constructed as the sum of five binary items, hence ranging in value for 0 to 5 (Alpha = 0.88). The items were: "new customers in our country"; "new customers in other countries"; "research centres similar to CERN"; "other large-scale research centres"; "other smaller research institutes".

Suppliers' performance was measured by the following variables (Table 4):

- *Sales-profits* is the sum of three binary items: "increased sales", "reduced production costs" and "increased overall profitability" (Alpha = 0.84). Its value ranges from 0 to 3 and measures suppliers' performance in terms of financial results.
- *Development* is the sum of three binary items: "Established a new R&D team/unit", "Started a new business" and "Entered a new market" (Alpha = 0.86). Ranging in value from 0 to 3, this var-

iable measures suppliers' performance from the standpoint of development activities relating to a longer-term perspective than sales–profits.

- *Losses and risk* is a binary variable taking the value 1 if the firm agreed or strongly agreed with the statement "experienced some financial losses" and 0 otherwise.
- *Second-tier benefits* is a variable constructed as the sum of four binary items (Alpha = 0.89) and thus ranges in value from 0 to 4. It captures outcomes within second-tier suppliers (Table 6).

We control for several variables that may play a role in the relationship between the governance structures and the suppliers' performance.

- *Firm's size* is coded as 1 if the supplier is small, 2 if medium-sized; 3 if large and 4 if very large.
- *Previous experience*. This is measured by three binary variables, whose value is 1 if the supplier ticked the corresponding option and 0 otherwise. The options were related to previous working experience with:
    - large laboratories similar to CERN (*experience with large labs*);
    - research institutions and universities (*experience with universities*);
    - non-science-related customers (*experience with non-science*);
- *Relationship duration* is calculated as the difference between the years of the supplier's last and first orders from CERN. It takes the value 1 if it is above the mean (5 years) and 0 otherwise.
- *Time since last order* is calculated as the difference between the year of the survey (2017) and the year in which the supplier received its last order. It takes the value 1 if it is above the mean (4 years) and 0 otherwise.
- *Geo-proximity* is a binary variable measuring whether the supplier selected its subcontractors on the basis of geographical proximity.
- *Country* is coded 1 if the supplier is located in a very poorly balanced country; 2 if the country is poorly balanced, 3 if it is well balanced. According to CERN's definition, a "well-balanced" member state is one that achieves "well balanced industrial return coefficients". The return coefficient is the ratio between the member state's percentage share of procurement and the percentage share of its contribution to the budget. Receiving contracts above this ratio means being well balanced; below, the country is defined as poorly balanced. CERN's procurement rules tend to favour firms from poorly balanced countries over those in well balanced countries.

Table 7. Econometric analysis: list of variables.

Variable	N	Mean	Min	Max
*EUR per order ****	669	0.34	0	1
High-tech supplier	669	0.58	0	1
Governance structures				
*Market****	669	0.27	0	1
Hybrid	669	0.53	0	1
*Relational****	669	0.20	0	1
*Governance***	669	3.72	0	5
Intermediate outcomes				
*Learning****	669	2.30	0	6
Innovation				
*New products ****	669	0.54	0	1
*New services ****	669	0.39	0	1
*New technologies****	669	0.27	0	1
*New patents-other IPR****	669	0.04	0	1
Market penetration				
*Market reference****	669	1.23	0	2
*New customers***	669	1.05	0	5
Performance				
*Sales-profits***	669	0.33	0	3
*Development****	669	0.28	0	3
*Losses and risk**	669	0.06	0	1
Second-tier relation variables				
Second-tier high-tech supplier	256	0.37	0	1
Governance structures				
*Second-tier market**	256	0.20	0	1
Second-tier hybrid	256	0.46	0	1
*Second-tier relational**	256	0.34	0	1
*Second-tier benefits**	256	3.14	1	4
Geo-proximity	256	0.48	0	1
Control variables				
*Relationship duration***	669	0.30	0	1
Time since last order	669	0.20	0	1
*Experience with large labs***	669	0.70	0	1
*Experience with universities**	669	0.85	0	1
Experience with non-science	669	0.96	0	1
Firm's size	669	1.83	1	4
Country	669	2.03	1	3

Asterisks denote statistical differences in the distribution of variables between high-tech and low-tech suppliers. ***p < 0.01; **p < 0.05; *p < 0.10. Depending on the distribution of variables, both Pearson's chi^2 test and Fisher's exact test were used.

4 The Results

4.1 Ordered logistic models

We used ordered logistic models to analyse correlations between CERN suppliers' performance and a set of determinant variables indicated by the PPI literature. Specifically, we looked at the impact of different governance structures on the performance of first-tier suppliers, controlling for their learning, innovation and market penetration outcomes and other order-specific and firm-specific variables. Table 8 and Table 9 report estimates of these regressions with *Sales-profits* and *Development* as dependent variables.

As column 1 in Table 8 shows, by comparison with the market interaction modes, the relational and hybrid structures of governance are positively and significantly correlated with the probability of increasing sales and/or profits. These variables remain statistically significant also when the model is extended to include some specific aspects of the CERN-supplier relationship (column 2). Given the structure of governance, a collaborative relationship between CERN and its suppliers in unexpected situations, enabling suppliers to access CERN labs and facilities, increases the probability of improving suppliers' economic results. Controlling for learning, innovation and market penetration outcomes (column 3), we find that the governance structures lose their statistical significance, while improvements in sales and/or profits are more likely to occur where there are innovative activities (such as new products, services, patents). Moreover, the strong significance ($p < 0.01$) of *Market reference* and *New customers* indicates that better economic results stem from the ability to exploit CERN as a "door opener" in the market. The role of these intermediate outcomes is confirmed even when other control variables are added (column 4). These results still hold when the binary governance structure variables are replaced by the *Governance* construct (Columns 5-7).

In Table 9 the dependent variable is *Development*. These estimates confirm the foregoing results with two differences. One is the very important role of *Learning* for developmental activities ($p<0.01$); the second is the effect of firm size: the larger the supplier, the greater the probability of establishing a new R&D team, new business or entering new markets ($p<0.10$).

The ordered logistic models provide interesting insights into the variables that affect suppliers' performance. In particular, they show that learning, innovation and market penetration outcomes are crucial in explaining the probability of increases in sales, reductions in costs, greater profitability or more developmental activities in CERN suppliers.

Table 8. Ordered logistic estimates. Dependent variable: *Sales-profits*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Governance structures							
Relational	1.17(0.27)***	0.96(0.29)***	0.38(0.36)	0.40(0.39)			
Hybrid	0.61 (0.24)**	0.43(0.25)*	0.13(0.31)	0.08(0.33)			
Governance					0.44(0.10)***	-0.06(0.28)	-0.14(0.29)
Access to CERN labs and facilities		0.43(0.18)**	-0.09(0.22)	0.07(0.24)		0.02(0.38)	0.27(0.41)
Knowing whom to contact in CERN to get additional information		0.27(0.32)	0.69(0.43)	0.73(0.46)		0.75(0.48)	0.88(0.51)
Understanding CERN requests by the firm		0.33(0.42)	-0.30(0.47)	-0.27(0.49)		-0.26(0.55)	-0.14(0.59)
Understanding firm requests by CERN staff		0.27(0.39)	0.26(0.48)	0.32(0.50)		0.32(0.61)	0.47(0.63)
Collaboration between CERN and firm to face unexpected situations		0.47(0.21)**	-0.09(0.28)	-0.17(0.30)		-------	-------
Intermediate outcomes							
Learning			0.14(0.06)**	0.11(0.06)*		0.15(0.06)**	0.11(0.06)*
Innovation							
New products			0.57(0.28)**	0.65(0.28)**		0.55(0.27)**	0.63(0.28)**
New services			0.67(0.27)**	0.60(0.28)**		0.69(0.27)***	0.62(0.27)**
New technologies			-0.01(0.28)	0.006(0.29)		0.00(0.27)	0.02(0.27)
New patents-other IPR			0.77(0.40)*	0.86(0.50)*		0.83(0.50)*	0.93(0.50)*
Market penetration							
Market reference			0.49(0.19)**	0.58(0.21)***		0.50(0.19)***	0.59(0.21)***
New customers			0.50(0.07)***	0.50(0.07)***		0.50(0.07)***	0.49(0.07)***
Euro per order				0.07(0.12)			0.07(0.12)
High-tech supplier				-0.04(0.27)			0.02(0.26)
Control variables							
Relationship duration				-0.02(0.02)			-0.02(0.02)
Time since last order				0.02(0.02)			0.02(0.02)
Experience with large labs				0.13(0.27)			0.17(0.27)
Experience with universities				-0.21(0.37)			-0.21(0.37)
Experience with non-science				0.15(0.75)			0.13(0.76)
Firm's size				-0.01(0.13)			-0.02(0.12)
Country				-0.20(0.12)			-0.19(0.11)
Constants	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	669	668	668	660	669	668	660
Pseudo R2	0.02	0.04	0.20	0.21	0.03	0.20	0.21
Proportional odds hp test (*p*-value)	0.911	0.294	0.220	0.02	0.285	0.123	0.00

Robust standard errors in parenthesis. ***,**,* denote significance at the 1%, 5% 10% level respectively.

Table 9. Ordered logistic estimates. Dependent variable: *Development*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Governance structures							
Relational	1.53(0.29)***	1.33(0.30)***	0.92(0.35)***	0.93(0.40)**			
Hybrid	0.62(0.27)**	0.46(0.28)*	0.17(0.33)	0.14(0.35)			
Governance					0.30(0.09)***	-0.28(0.30)	-0.26(0.31)
Access to CERN labs and facilities		0.46(0.20)**	-0.35(0.26)	-0.25(0.28)		0.04(0.41)	0.13(0.42)
Knowing whom to contact in CERN to get additional information		0.61(0.41)	0.86(0.48)*	0.92(0.56)		1.01(0.65)	1.11(0.65)
Understanding CERN requests by the firm		-0.19(0.42)	-0.46(0.48)	-0.33(0.56)		-0.19(0.54)	-0.06(0.64)
Understanding firm requests by CERN staff		0.12(0.43)	-0.05(0.49)	-0.04(0.57)		0.27(0.60)	0.27(0.66)
Collaboration between CERN and firm to face unexpected situations		0.39(0.21)*	-0.31(0.30)	-0.30(0.31)		-------	-------
Intermediate outcomes							
Learning			0.36(0.07)***	0.33(0.07)***		0.36(0.07)***	0.32(0.07)***
Innovation							
New products			-0.01(0.27)	-0.05(0.29)		-0.07(0.27)	-0.03(0.28)
New services			0.60(0.28)**	0.68(0.29)**		0.57(0.27)**	0.68(0.28)**
New technologies			0.08(0.29)	0.10(0.30)		0.16(0.28)	0.16(0.28)
New patents-other IPR			1.02(0.48)**	1.00(0.53)**		1.20(0.49)**	1.19(0.50)**
Market penetration							
Market reference			0.53(0.21)***	0.47(0.21)**		0.60(0.21)***	0.54(0.21)***
New customers			0.19(0.08)**	0.20(0.08)**		0.18(0.08)**	0.18(0.08)**
Euro per order				0.09(0.12)			0.07(0.12)
High-tech supplier				0.00(0.28)			0.12(0.27)
Control variables							
Relationship duration				-0.04(0.02)			-0.04(0.02)
Time since last order				-0.03(0.03)			0.03(0.03)
Experience with large labs				0.20(0.29)			0.20(0.29)
Experience with universities				-1.00(0.34)***			-0.98(0.35)
Experience with non-science				0.14(0.64)			0.13(0.63)
Firm's size				0.18(0.13)			0.20(0.11)*
Country				-0.21(0.13)			-0.21(0.12)*
Constants	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	669	668	668	660	669	668	660
Pseudo R2	0.03	0.04	0.18	0.20	0.01	0.16	0.18
Proportional odds hp test (*p*-value)	0.931	0.235	0.217	0.020	0.431	0.601	0.003

Robust standard errors in parenthesis. ***,**,* denote significance at the 1%, 5% 10% level respectively.

4.2 Bayesian Network analysis

In order to shed light on all the possible interlinkages between variables and look more deeply into the role of governance structures in determining suppliers' performance, we use BN analysis, which makes it possible to visualise and estimate all direct and indirect interdependencies among the set of variables considered, including those relating to the second-tier suppliers. We test the four hypotheses that underlie our conceptual framework and seek to disentangle the specific roles played by governance structures, intermediate outcomes and firm-specific and order-specific characteristics in determining firms' performance.

Figure 2 shows the DAG of a BN where the governance structure is measured by the three binary variables *Relational*, *Hybrid* and *Market;* in Figure 3, instead, the variable used is *Governance*. Both the BNs were estimated by applying the Bayesian Search algorithm (Heckerman et al., 1994). The strength of the relationship between the variables is indicated by the thickness of the arrows: the thicker the arrow, the stronger the dependency. Variables showing no links are excluded from both graphs.

Figure 2 shows that both status as a high-tech supplier (i.e. providing CERN with highly innovative products/services) and the size of the order play a direct role in establishing both *relational* and *hybrid* interaction modes, in line with Hypothesis 1**.** By contrast, there are no strong links with the market-type governance structure.

The BNs also confirm Hypothesis 2: innovation (i.e. new products, new services, new technologies and new patents) and learning outcomes depend directly on relational-type interactions. Actually, the variable *Relational* is strongly correlated with the development of new technologies and new products, whereas market-type governance is linked to the use of CERN as marketing reference or gaining increased credibility on the market, which corroborates the idea that the fact of having become a supplier of CERN is likely to produce a reputational benefit.

Some linkages among the intermediate outcomes emerge, suggesting that the cooperation with CERN spurs several changes in suppliers' propensity to innovate. The DAG shows that learning outcomes (e.g. improvements in technical know-how as well as in R&D and innovation capabilities) are associated with developing new technologies, while developing new patents and other IPR is linked to the acquisition of new customers.

These intermediate outcomes are expected, in turn, to be associated with better firm performance (Hypothesis 3). This correlation, which the ordered logistic models documented, is confirmed and further qualified by the BN analysis. In fact, the development of new products and the acquisition of new customers are linked chiefly to an increase in sales/profits, whereas new patents and other forms of IPR lead not only to higher sales/profits but also to a greater probability of developmental activities. The BN analysis also shows that the variables that measure suppliers' performance are strongly linked with one another, suggesting that the result tends to be an overall enhancement of firms' performance, rather than gains involving specific aspects.

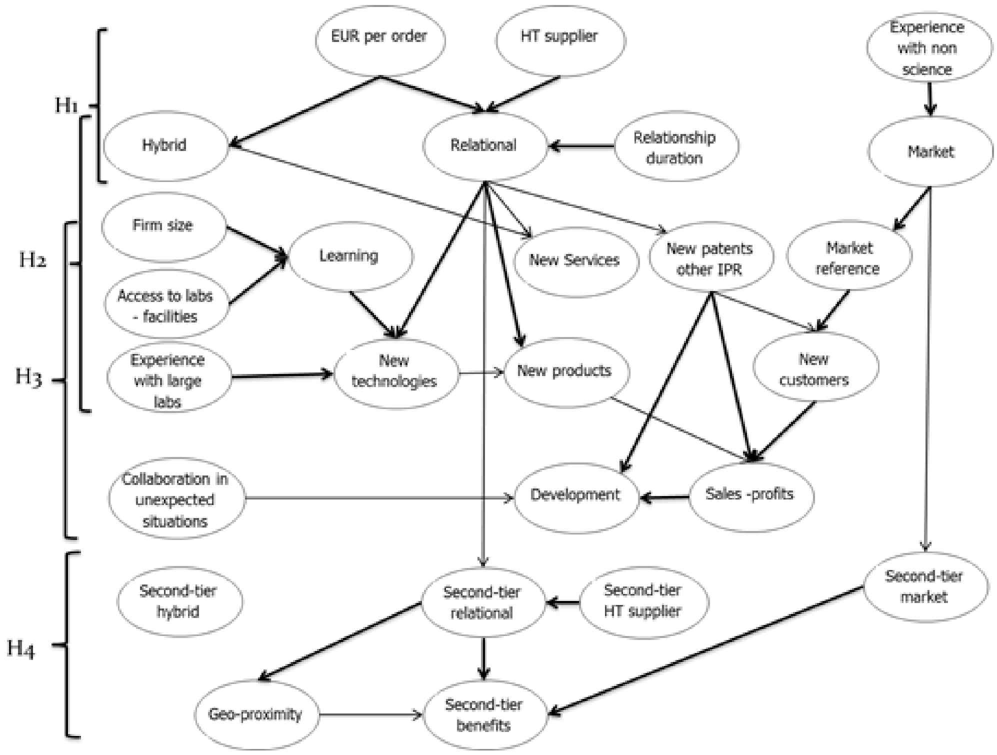

Figure 2. Bayesian Network: the impact of different types of governance structures on firm performance. Governance structures are proxied by three binary variables: Relational, Hybrid, and Market.

Hypothesis 4 is tested in the bottom of the DAG, where we look at the modes of interaction between first-tier and second-tier suppliers and the potential benefits accruing to the latter. The BN highlights a positive correlation between the governance structures and benefits for subcontractors, as perceived by CERN's suppliers. An examination of the DAG as a whole clearly shows that the type of first-tier relationship between CERN and its direct suppliers is replicated in the second-tier relationships established between direct suppliers and subcontractors. This holds for both relational governance structures (the arc linking *Relational* and *Second-tier relational*) and market structures (the arc linking *Market* and *Second-tier market*). Presumably, what drives this process is the degree of innovation and the complexity of the orders to be processed: supplying highly innovative products requires strong relationships not only between CERN and its direct suppliers but also between the latter and their own subcontractors in order to deal effectively with the uncertainty inherent in the development of new technologies at the frontier of science, where the risk of contract incompleteness and defection is very high. Finally, it is worth noting the role of some control variables. Firm's size is linked to the learning outcomes, which in turn related to innovation outcomes. As Cohen and Levinthal (1990) suggest, access to the network by suppliers is a necessary but not sufficient condition for learning, which rather depends on the firm's absorptive capacity. Large firms are more likely to absorb external knowledge and benefit from the supply network, because with respect to smaller companies they generally have higher levels of human capital and internal R&D activity, as well as the scale and resources required to manage a substantial array of innovation activities (Cano-Kollmann et al., 2017). Moreover, previous experience working with large-scale labs similar to CERN is positively associated with the development of new technologies. By contrast, the suppliers whose previous experience was with non-science-related customers are more likely to establish market relationships with CERN. The DAG also shows that the possibility of accessing CERN's research facilities is linked to the development of new technologies, while collaborative behaviour in unexpected situations heightens the probability of carrying out development activities.

This leads us to the network in Figure 3, where the variable *Governance* encapsulates these specific aspects of the supply relationships. The DAG confirms the main relationships discussed above; that is, the higher the value of the variable *Governance*, the greater the benefits enjoyed by CERN suppliers.

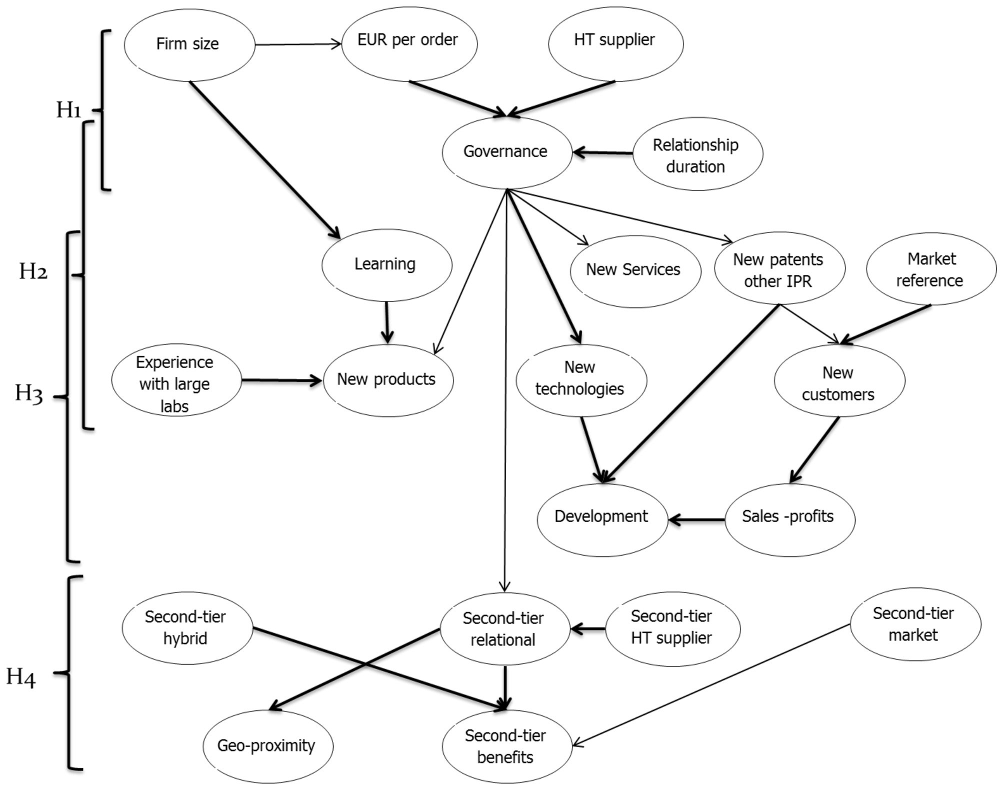

Figure 3. Bayesian Network: the impact of different types of governance structures on firm performance. Governance is proxied by a five-item construct as described in Section 3.4.

The robustness of the networks was further checked through structure perturbation, which consists in checking the validity of the main relationships within the networks by varying part of them or marginalising some variables (Daly et al., 2011; Ding and Peng, 2005).[5]

5 Conclusions

This paper develops and empirically estimates a conceptual framework for determining how government-funded science organisations can support firms' performance through their procurement activity. By exploiting both logistic regression models and Bayesian Network analysis on CERN procurement, we find that: *i)* the learning, innovation and market penetration outcomes achieved by suppliers impact positively on their economic performance and development; *ii)* the suppliers involved in structured and collaborative relationships with CERN turn in better performance than companies involved in pure market transactions characterised by little or no cooperation. As our BNs reveal, relational-type governance structures channel information, facilitate the acquisition of technical know-how, provide access to scarce resources and reduce the uncertainty and risks associated with complex projects, thus enabling suppliers to enhance their performance and increase their development activities. These relationships hold not only between the public procurer and its direct suppliers but also between the latter and their subcontractors, suggesting that benefits spill over along the whole supply chain.

Our findings are relevant both for policy makers and for Research Infrastructure managers. Given the large scale and complexity of RIs, parties are often unable to precisely specify in advance the features of the products and services needed for the construction of such infrastructures, so that intensive, costly and risky research and development activities are required. In this context, procurement relationships based solely on market and price mechanisms are not a suitable instrument for governing public procurement, as they would not be able to deal with the uncertainty embedded in innovation procurement. Instead, if parties cooperate during contract execution, and specifically if a relational governance structure is established, not only are the requisite products and services more likely to be developed and delivered, but additional spill over benefits are generated in supplier firms. The patterns of these relationships across members of the supply network influence the generation of innovation, helping to determine whether and how quickly innovations are adopted so as to produce performance improvement in firms.

In addition, we looked at suppliers "from within", and our results highlight that firms' heterogeneity is an important factor. The impact on suppliers' performance produced by CERN procurement depends critically on firm size, on status as high-tech supplier, and on an array of other factors, including the capacity to develop new products and technologies to attract new customers via marketing, and the ability to establish fruitful collaborations with subcontractors.

These results could help public science organisations to identify the most appropriate mode for carrying out their mission as a learning environment and policy makers to better design demand-side mission-oriented policies such as public procurement for innovation. Future research is needed for broader and more in-depth inquiry into the effects of RI-related public procurement on second-tier suppliers and possibly other levels of the supply chain.

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[1] This work was supported by the European Organization for Nuclear Research (CERN) and the University of Milan '[grant number FCC-151111-CERN_FCC-MoU_UNIMI]' and Centre for Economic and Social Research Manlio Rossi-Doria, Roma Tre University.

[2] Major examples of large-scale RIs are the International Space Station, the Square Kilometre Array, the Human Genome Project and the last generations of large-scale particle accelerators and colliders. De Solla Price (1963) coined the term "Big Science" to describe the large-scale character and complexity (i.e. the technological and engineering challenges and the capital-intensive research projects) of modern science, in contrast to the old "Little Science".

[3] Names in brackets are those formulated by Gereffi et al. (2005), who elaborates on Williamson (1991) and renames government structures as market, modular, relational, captive, and hierarchy. In this paper we adopt the Gereffi et al. (2005) classification.

[4] Like similar previous studies (Schmied, 1977; Bianchi-Streit et al., 1984), ours excludes the smallest orders. This threshold, corresponding to CHF 10,000, was agreed with CERN procurement office.

[5] The size of the respondent firms is taken from the Orbis database. Very large firms are those that meet at least one of the following conditions: Operating revenue >= EUR 100 million; Total assets >= EUR 200 million; Employees >= 1,000. Large companies: Operating revenue >= EUR 10 million; Total assets >= EUR 20 million; Employees >= 150. Medium-sized companies: Operating revenue >= EUR 1 million; Total assets >= EUR 2 million; Employees >= 15; Small companies are those that do not meet any of the above criteria. Orbis data on size were missing for 34 supplier companies in our sample, but we retrieved the size of 25 from their websites. The size of the remaining 9 companies is missing.

[6] Respondents could select up to two options.

[7] For this question, respondents could select up to two options. A total of 710 responses were received.

We test the networks upon different sets of variables, and we alternatively included the original variables in the questionnaire or more complex constructs summarising one or more of the original variables. Further tests, where control variables were alternatively included or were not, were also performed. These checks show that the main relations presented in the BNs remain stable enough.