Organization Theory and High Energy Physics (HEP) Mega Laboratories

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Abstract

The organization of cutting-edge HEP mega laboratories has evolved in the intersection of academia, state agencies, and industry. Exponentially ever-larger and more complex knowledge-intensive operations, the laboratories have often faced the challenges of, and required organizational solutions similar to, those identified by a cluster of diverse theories falling under the larger heading of organization theory. The cluster has either shaped or accounted for the organization of industry and state administration. The theories also apply to HEP mega laboratories, as they have gradually and uniquely hybridized their principles and solutions. Yet scholarship has virtually ignored this linkage and has almost exclusively focused on the laboratories' presumably unique organizational aspects. We offer a preliminary roadmap for the analysis of the organization of HEP laboratories against various, often conflicting, principles of the organization theory cluster, as well as a preliminary consideration of these principles as the basis for the assessment of the laboratories' performance.

Keywords: Organization Theory; Management studies; Decision Theory; Scientometrics; Operation Theory; Division of Labor; High Energy Physics Laboratories; Weber.

1. **Introduction**

The main goal of this paper is to offer a general account of suitable criteria to assess the organization and performance of particle physics mega laboratories. These are cutting-edge scientific institutions in terms of the experimental work they perform, the funds multiple states invest in them and the employment opportunities they provide for physics researchers. They are also unique in terms of the organizational structures they harbour. The success of the former depends largely on the adequacy of the latter.

In general, the optimization and efficiency of scientific institutions emerged as a major issue during WWII when the symbiosis of the military and physics led to the rise of big laboratories, notably in the concerted effort to design an atomic bomb. Over the years, tying the assessment of the performance (i.e., the production of knowledge) of mega laboratories to optimal ways of organizing them has gradually become a requirement of governments, their main funders. This cannot be done, however, unless there are clear criteria of performance. Such criteria are also the basis for understanding how generating scientific knowledge in the setting of mega laboratories compares to performance in more traditional settings. But how exactly does one organize a mega laboratory in order to achieve its optimal performance in the production of relevant knowledge? Or more precisely, what organizational principles will ensure optimal performance of a mega laboratory with respect to a particular set of goals.[1]

As mega laboratories have been around for 75 years and receive vast sums of public money, it is surprising that their management has not been a topic of more serious study.

[1] Thus, organizational principles are inextricably tied to the examination of the performance criteria. Performance criteria depend on the institution's goals. For instance, does the laboratory need to fulfil larger public goals (e.g. educational goals or development of new technologies), vague scientific goals set by the funders (i.e. by government agencies), the goals set by the designers of the laboratory, the usually narrow goals set by the in-house team, or the goals of external research groups working on the in-house experiments that battle for funding? Measuring performance of each of these goals requires different metrics, and each of these goals is served best by a particular organizational structure.

Although “the division of labour and its management in science have become more important since the sizes of research teams have increased, this aspect of the management of science has not yet been addressed by research” (Murayama et al. 2015, 864). Furthermore, “[e]ven though the literature on the economics of science has grown… the study of the management of science has been quite limited. The management of science has not yet been well investigated in management studies” (Ibid.). Finally, “[o]rganizational studies have largely ignored scientific inter-organizational collaborations as objects of inquiry” (Chompalov et al. 2002, 750).

A logical way to approach the topic is through organization theory. This is not so simple for HEP mega labs. A mega laboratory typically embodies a hybrid collection of organizing principles, often at odds with each other and realized across laboratories. However, the common thread is that their organization typically follows the principles of organization theory found in industry and state administration. This is not surprising, given the close ties of industry and government to the research performed in such labs. Philosophers, anthropologists, and science policy experts (Galison and Hevly 1992; Cetina K. 2009; Martin and Irvine 1984a, 1984b, 1985; Perović 2016) have analyzed some aspects of the organization of HEP mega laboratories, but studies of the explicit connections between the organization theory dominating the development and the study of industry and state administration, on the one hand, and the organization and management of large scientific institutions, on the other, are lacking. As I see it, such studies are essential to understand the workings of modern HEP laboratories. The aim of the analysis, then, is to comprehensively identify the basic general features of the organization of HEP laboratories and determine the possibility of assessing their performance (i.e., their output) based on those features, thus motivating further quantitative and qualitative studies. The Organization Theory is a useful guide to identification of such features and to the study of the overlap between organizational features and principles in HEP laboratories and industry. Thus: 1) we identify the basic organizational features and its variations with the help of distinctions in organization theory, and the way they are related to projected epistemic goals, 2) we also identify what several authors deemed unique features of organization HEP laboratories (its egalitarian aspects) as rather usual occurrence in large, bureaucratized and knowledge-intensive institutions identified early on and studied in organization theory, and finally 3) provide general criteria for the assessment efficiency of knowledge production with respect to identified organizational structures and their basic features.

2. Preliminaries:The relevance of organization theory for understanding organization of HEP laboratories

2.1 HEP laboratories and their development

After quantum revolution in the 1920s new insights into the structure of matter required particle collisions at substantially higher energies than could be achieved in table-top experiments with fairly simple experimental apparatus' run at energies we experience in various everyday physical processes. The particle accelerator technology where particles are accelerated in an electromagnetic field and then smashed against a fixed target was initiated in by Ernest Lawrence's laboratory. It was in effect the first HEP laboratory and it was already run as a small industrial enterprise due to the size and complexity of the apparatus.

These laboratories have been constructed to test latest hypotheses on the structure of subatomic matter (particles and forces), a collection of which has been known as the Standard Model of particle physics since early 1970s. Also, besides testing of pre-set hypotheses the experimental results have often extended the Standard Model in unexpected ways. The final intended product of the laboratories – i.e. their narrow epistemic goal - has been primarily the results of the experiments published in external manuscripts in relevant journals, although internal laboratory publications have played increasingly significant role due to overlapping of tasks and team members between the laboratories. There is also a broader epistemic goal that emerged with the substantial increase in their size that concerns production of public (non-expert knowledge), teaching and other public activities.

In our analysis of their organization and epistemic goals they pursue we will rely on available historical, sociological, and anthropological accounts of HEP laboratories that were cutting edge at the time of their inception. This means that they could potentially deliver novel experimental knowledge about the structure of matter at the highest available energies at the time and were designed, constructed, and commissioned with that purpose in mind. (A number of HEP accelerators for industrial purposes have been constructed but their aim was rather different.) We will thus focus on and discuss typical and well documented cases and features.

The production of experimental knowledge in the laboratories can be traced surprisingly accurately by tracking the production of papers and citation counts. (see Martin and Irvine 1984b; Perović et al 2016) The HEP record of papers and citations INSPIRE has been established in the early 1970s. Citation counts in the field are as accurate a measure of productivity as it comes in a scientific field. They are cited in a very closed circle of experts: 1) oversight of relevant work is virtually impossible since there are only a handful of labs that collaborate 2) the papers are not cited in any significant rate outside the narrow field of particle physics so citation counts indicate the expert opinion alone. Thus they in effect trace the agreement between the experts on the validity and fruitfulness of the results.

Already in the late 1950s physicists realized that they will need unprecedented scale of funding in order to probe matter at ever higher energy levels. (Greenberg 1970, 209) Thus, the energies at which particles have been collided have grown exponentially (see Kragh 2002, 303 for the exact data on the growth), and with it the size and the cost of the apparatus, as well as the number of physicists and engineers that design and run it. The particle beam energy has increased by seven orders of magnitude since Lawrence's laboratory produced the first beams (Panofsky 1994, 128). The cost of energy production in accelerators per energy units decreased by five orders of magnitude, which means that the overall cost of accelerators that can produce required energies in particle collisions has increased by 10-100 times. (Ibid.) We need to add the cost of human resources to this. Early HEP laboratories employed a dozen, or a few dozen researchers, while currently Fermilab, one of the major HEP laboratories, employs 1750 regular staff, and hundreds of external collaborators working on projects performed in the laboratory.[2] Recent papers reporting discoveries and measurements coming out of CERN number between three and five thousand physicists.

Taking all this into account we can understand an extent to which HEP laboratories have grown since the inception. This growth happened fast in the first two decades after the WWII, but then it slowed down when the cost of laboratories' approached the above-stated level. In fact, the first phase of he growth occurred before particle colliders colliding accelerated beams inside a

[2] For the number of physicists working in HEP labs in previous decades see Martin and Irvine (1984a, 192) and pp.193-4 of the same publication for the estimated cost of each major laboratory.

detector, rather than it hitting a fixed target can be characterized as big-science HEP, similar in scale to some other large enterprises in science. With the rise of colliders at the end of the 1960 the size and the cost of individual colliders marks a new phase of mega-laboratories[3], reducing the number of those that can produce cutting-edge physics to only a handful (a dozen of lepton colliders, and six hadron colliders that could achieve substantially higher energies)[4] to currently a single one, The Large Hadron Collider (LHC) at CERN.

The organizational development of HEP laboratories[5] after WWII can be divided into three phases. The first phase comprises the years of WWII, with the Manhattan project for the construction of the atomic bomb being the major research work of the period and the Los Alamos laboratory as the place where major research for the project was done. (Hoddeson 1993) A fact crucial for understanding the first phase is the sheer number of leading experimentalists, including future directors of HEP laboratories, such as L. Alvarez, R.R. Wilson, L. Lederman, A. Weinberg and others, who were closely involved in the Manhattan project. In fact "[i]t would be perhaps easier to list those [physicists] who did not [work in the project], for it included most of the Western world's most brilliant physicists from legendary figures like Bohr to young and up-and-coming physicists like Richard Feynman" (Kragh 2002, 268). The organization of the

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[3] This sound distinction was drawn by Hoddeson et al. (2008)
[4] For a list and location of major HEP laboratories that produced collisions at energies in excess of one billion electron-volts see Panofsky (1994, 93). For an exhaustive list of laboratories prior to Large Hadron Collider at CERN see Martin and Irvine (1984a, 1984b, 1985). For an exhaustive list of all HEP related institutions see: http://slac.stanford.edu/spires/institutions/major.shtml. For a complete list of HEP cutting-egde laboratories see https://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics.
[5] In the US most prominently: Lawrence Berkeley National Laboratory (LBL), Stanford Linear Accelerator Center (SLAC), Brookhaven National Laboratory (Stoney Brook), Fermilab. In Europe: CERN (Switzerland), Frascatti (Italy), and HERA (Germany). KEK in Japan and Dubna in Russia/USSR.

project and Los Alamos laboratory was a novel symbiosis of the military and the scientific community operating in a university setting (Hoddeson 1993; Greenberg 1970). In his classical theory of state bureaucracy, arguably the most influential work in the sociological strand of organization theory, Weber (1958) accounts for the basic elements of the administrative structure and organization of the military later employed in the Manhattan project, showing how it overlaps with the principles guiding large private enterprises.

Also important in the first phase was the founding of CERN (Conseil Européen pour la Recherche Nucléaire). Conceived as a multinational institution, it was deliberately organized in a top-down fashion with a directing committee established to closely control all phases of the operation to balance the interests of participating nations (Hermann et al. 1987). In addition, various measures of organizational efficiency were introduced into US military projects during the war and developed with the help of simulations and modeling; this laid the foundations for the Rational Modern strand of organization theory (Beer 1959).

Thus, the first directors and managers of major HEP laboratories learned their craft in an environment that combined the organizational principles on which state and military organizations were based, and they were trained in the need to measure and improve their efficiency. Despite these commonalities, they went on to establish quite diverse organizational structures in the HEP laboratories of the 1950s.

During the second phase, the early 1960s to the 1980s, laboratories exponentially increased in size and complexity, becoming what we now call mega laboratories. Various organizational principles and management styles converged with those developed in industry and state administration. The very ambitious projects realized in the laboratories required close cooperation with industry, necessitating mutual organizational adjustment. This was true even for the first mega laboratories in the 1950s. For example, when discussing a CERN project recently, one commentator said, “The construction of ATLAS [one of two major detectors at the Large Hadron Collider at CERN] is an industrial-scale undertaking, and the collaboration therefore has to turn to industry for help” (Boisot et al., 2011, 4). Despite the specificity of the environment of mega laboratories compared to industrial enterprises, their directors faced some of the same challenges and had to come up with similar responses.

At the same time, the state was channeling ever-increasing funds towards the big laboratories, understandably raising questions about whether the (public) money was being spent wisely. By 1964, US Congress had already expressed doubts about whether scientists were the best kind of personnel to manage and run big scientific projects (Marburger 2015, 47). The fact that the state was the major funder resulted in the assimilation of organizational principles dominant in state institutions, thus adding another layer to an already hybrid structure.

Outside the labs, a fully professionalized management class was successfully running large industrial projects by then, while state institutions had been run by professional administrators for quite some time. And this new management class was educated in various forms of organization theory.

During the third phase, the 1980s to the present, the rise of large colliders substantially increased the complexity of a few key laboratories. These laboratories overshadowed the rest in terms of the capacity for cutting-edge experiments at the highest collision energies available. Concomitantly, a class of professional managers with MBA and related degrees (e.g. project management) emerged .[6] In addition, a formal management system was introduced in the US by Department Of Energy for large projects, the largest ones being high energy physics laboratories

[6] See section…; see also affiliations and education of authors n Boisot et al. 2011

(Marburger 53). At this point, managers outnumber researchers in some departments of HEP laboratories and often micromanage their tasks.[7]

The large industrial and state projects, on the one hand, and mega HEP laboratories, on the other, share some obvious interests but they also share certain key constraints. They are continuous balancing operations where decisions are made in the face of pressures exerted by funders, constraints of human limitation that have to be made up for (e.g. a need to constantly and exponentially increase computational capabilities crucial for research), limits of cooperation of large numbers of professionals, and physical limits (e.g. collaboration across multiple geographical locations) (Barnard 1938; Peltonen 2016, 74).

They also have similar evolutionary trajectories. In the economy in which small businesses dominate, the fate of a business is not decided by ingenious ways of handling the division of labour, as it is in the setting of industrial mass production. The transition in physics laboratories followed the same trajectory as 20th century industry when laboratories started to evolve from handling logistical operations performed by one or two researchers at the beginning of the 20th century (with occasional exceptions in the history of physics) to employing dozens, hundreds, and recently thousands of scientists and technical staff.

Recent forensic analyses of the failed SSC project (Riordan et al. 2015, Marburger 2015) reveal crucial similarities between the environment in which planning and design of large laboratories takes place and the environment in which large industrial projects are realized. The accounts of managers of the laboratories are especially useful sources to explore such

[7] This insight is based on recently conducted interviews with the physicists of various seniority at Fermilab and CERN.

similarities[8], as are detailed histories of laboratories (e.g. Hoddeson et al. 2008). Finally, in longitudinal studies, anthropologists embedded in the HEP community report some typical aspects of the organizational challenges we find in industry (Traweek 2009). In any case, the development of HEP mega laboratories represents a symbiotic linking of corporate, state, and scientific organizations and their goals. Consequently, the general features of organization and management in HEP laboratories reflect those of their partners.

2.2 Is organization theory applicable to understanding organization of HEP laboratories? Are they a special case?

Organization theory refers to a cluster of theories that emerged out of industrial practice and academic and professional management studies of organization of industry and state administration.[9] The theories within the cluster can be grouped into Classical Organization Theory, Cultural Modern Theory, Rational Modern Theory, Structural Contingency Theory, and a sociological strand that started with Weber. These various strands of organization theory offer a powerful tool for understanding the way modern mega laboratories performing experiments in particle physics are organized.

The organization and the goals of production are always intrinsically related in Organization theory: certain organizational principles are implemented in order to provide a desired form of production (e.g. a steady production, or production boosting short-term profits).

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[8] For example see the accounts of Alvarez (1968), Marburger (2015) and (Hoddeson et al 2008) for an exhaustive list of R. R.Wilson’s accounts.

[9] In dividing and grouping various theories of organization, I rely on a wonderful and informative review of organization theory and its history by Peltonen (2016). There are many excellent historical accounts and classifications of organization theory each focusing on particular strands. But I focus on those relevant to the organization of HEP mega laboratories; in this sense, Peltonen’s classification is helpful and comprehensive. It is certainly possible that other work may be relevant, but this is a preliminary account meant to motivate further studies.

Similarly, a key feature of organizing a HEP laboratory is its epistemic goal which can be either narrow or broad. The organization and the goals related to the production of knowledge in a laboratory are intrinsically connected[10]: the principles that define the organization will in turn define its production of knowledge, and vice versa. Our goal is to understand the organizational feature of HEP laboratories by identifying them with the help of Organization theory, as they have been developed to fulfil particular epistemic goals, and to examine how such goals and organization have affected each other.

Yet before we turn to identifying the elements of organization common to mega laboratories, industry and state institutions, it is instructive to look at an instance of the self-perception of the HEP management community on this issue. How does that community see itself in relation to the influence of the state as the funder and industry as a major partner and a prototype of organization and management of large projects? At a workshop held at CERN and sponsored by ATLAS management and its project leaders, a group of professional physicists-managers put together an exhaustive analysis, a self-assessment of sorts, of the organizational structure of HEP (CERN in particular) and its adequacy to achieve set goals (Boisot et al. 2011, 3). The general impression was fairly optimistic in terms of the capability of handling organizing tasks by pursuing autonomous management approaches (albeit from state and industry principles).

The group never explicitly reflected on organization theory but aimed at developing particular models to understand the organizational setting and challenges of HEP.[11] One specificity of the organization of large HEP laboratories, they pointed out, is shared with other

[10] See Torrisi (2014) for an in-depth discussion of various criteria of productivity in science.

[11] Another telling example of an overly optimistic view of the management of mega laboratories is the unconditional perception of open-science, especially resource aggregation as benefiting research. The limits of aggregation have been extensively studied, and the results suggest that aggregation can fairly quickly start affecting performance negatively for a number of reasons.

knowledge-intensive organizations in industry and government – the business of research and development (R&D). In fact, the goals and structures of R&D departments in industry closely resemble those of HEP laboratories. Typically, these organizations evolve in somewhat unpredictable ways; they rely on research and innovation and, thus, continuously deal with organizational uncertainties (Boisot et al. 2011, Ch.5). Yet the design, commissioning, and performance of mega laboratories is so broad that it encompasses all the stages of a modern industrial project and its organization, not just its R&D department.

We will argue that despite the somewhat justified attitude that "the managers of knowledge-intensive organizations may have more to learn from how Big Science projects such as ATLAS are developed and run than the other way around" (Boisot et al. 2011, 25), the organizing principles of HEP labs are, to a large extent, deeply entrenched in the practices of industry and state, even though they have hybridized them. In fact, it is difficult to see how we can fully understand the organization of HEP laboratories without considering how organization theory has been applied in industry and government.

It should be noted that the notion of the exceptionalism of HEP laboratories in particle physics as uniquely egalitarian scientific institutions with little or no hierarchy (Chompalov et al. 2002; Cetina K. 1999; Galison and Hevly 1992; Krige 1991) is often spelled out too generally and it may be misleading. There is certainly such an aspect to the organization of HEP laboratories, and this has been explored in depth from various angles.[12] The reasons for its emergence are fairly clear:

[12] See especially Chompalov et al. (2002) where extensive interviews are conducted with researchers across physical science, including those working in HEP laboratories. The results show a loose administrative structure in HEP laboratories compared to other sub-fields, but this does not necessarily mean the patrimonial organizational structure of research is as loose.

> Competition for time and space at accelerator laboratories, routinized institutional politics, and the limited range of experimental styles heightened the competition for making discoveries and for testing theories. These conditions imposed extraordinary discipline that pushed collaborators to adopt similar organizational structures, granting broad rights of participation to all members of the collaboration, from graduate students to senior faculty. Such Athenian-style democracy has produced remarkably successful outcomes. (Chompalov et al. 2002, 751)

Yet these laboratories are much more complex institutions than the last sentence of this passage and other accounts suggest[13]. And as Section 3.3 goes on to show, this egalitarian aspect is a regular occurrence in large institutions with a vast administrative structure – it's just that HEP laboratories are a rare example of it in experimental physics and science in general. Thus, as we will see, first, this organizational aspect is only a moderate loosening or flattening of a complex hierarchical organizational structure the features of which we will identify with the help of organization theory. It is an epiphenomenon of complex bureaucratized institutions which inevitably eventually emerges due to the increase in their size and thus should not be deemed a central organizational feature. And second, the organization characterized by features various aspects of Organization theory will reveal, loosens/is mitigated in all knowledge-intensive institutions, including HEP laboratories, and is often deemed as an impediment to their efficient performance.

As we will see, many important aspects, the laboratories are far from being egalitarian paradises. Once we analyze the their organizational structure with the help of insights in organization theory, it may not be too surprising that, in fact, a number of leading figures in the

[13] There are also substantial differences between the organizations of various laboratories, as well as differences in different phases of their development. They started as either temporary establishments organized around multiple projects or as centralized in-house run laboratories, but they all evolved into long-term standing institutions.

HEP community, including D. Glaser, L. Alvarez, A. Weinberg, and R.R. Wilson (Krige 1991, 4) thought of a mega laboratory as an industrial factory-like environment that stifles creativity. The organization of HEP laboratories may be somewhere between an imagined egalitarian paradise and factory drudgery - exactly the position of the organization of most sophisticated industrial projects. The authors arguing for exceptionalism tend to contrast the environments of the laboratories with a caricatured image of similar operations taking place in industry. Thus, for instance, Krige (1991, 10) praises the mutual respect of professionals in the HEP labs as a mark of egalitarianism, even though, as we have noted, such respect is customary in industry as well. Exaggerating the egalitarian aspect may conceal the actual structure, which can be particularly detrimental if we believe in an egalitarian ideal of organizing science. In fact, such rather hasty conclusions show deficiencies of the analysis that overlooks the key organizational features we will identify with the help of organization theory. The analysis based on the organization theory is not only a supplement to the existing studies but a richer framework providing a more nuanced picture.

3. **Basic principles of the organization theory cluster in relation to the organization of major HEP laboratories**

3.1 Classical organization theory; industrialization of knowledge production in HEP laboratories

Classical organization theory focuses mainly on the organization and division of labour in industry, but emerging analysis from the sociological perspective expands this to a wider range of modern Western institutions. The former analysis was developed out of practical necessity by industry practitioners as a normative tool for industry, and taken up by professionals specializing in the field of organizational tasks. The latter was a result of academic reflection on existing organizational and administrative structures. They converge on a number of issues, however. First, they both analyze institutions as organizational wholes and focus on identifying their various key functions. Second, they study various styles of management and their impact on the efficiency of institutions. Third, they track the influence of a wider social and economic environment on the organization. Finally, and more importantly for present purposes, they both provide criteria to assess institutional performance for policy purposes.

Classical organization theory was conceived around the goal of optimizing productivity. A major insight in terms of raising productivity was that workers should not choose their tasks but perform tasks pre-planned by management; in this view, full work effort is best achieved through top-down management of smaller specialized tasks (Taylor 1919). This approach advocates a strict division of labour between workers and management, with managers requiring specialized skills different from those of the workers involved in the production. Thus, the rise of productivity crucially depends on establishing a hierarchy with a distinct skilled class of managers. Further development of the theory (Fayol 1949) suggests that the way to optimize the managerial work itself is to split it into segments and essentially treat it as production.

Taylor applied his ideas in the Bethlehem Steel Works where he worked as a consultant. (Taylor 1911) Further development of his classical principles by Henry Gantt (1974) were famously applied by Ford in his Detroit car manufacturing plants. Similarly, Fayol managed a mining company based on his principles. (Cohen 2003) The principles of classical management proved successful in these initial applications[14] and have been relied on in similar contexts across industries.

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[14] For critical assessments of early Taylor's accounts of his early experiments based on his principles of organization see Wrege and Perroni (1974).

Production increased exponentially with the widespread implementation of the new organizational principles, and the theory had to grow to accommodate the expanding operations:

> As the organization grows, and as the operations become diversified, the informal organizational model built around the entrepreneur will experience external pressure. The entrepreneur can no longer control all of the information. They can no longer be familiar with all members of staff, as the organization increases in size. Operations expand geographically, and direct contact with various offices is no longer possible like it used to be. (Peltonen 2016, 50)

Thus, optimal operation requires a closely-knit and well organized hierarchical network of managers and administrative staff following the basic principles of organizational theory.

Over time, the success of industrial organizations led to their expansion globally, but multinational corporations require a more flexible organizational and management structure; a matrix, as opposed to a strict hierarchy, can provide efficient communication and coordination of relatively loose groups and adequately position the organization in a large, diverse and often volatile international environment. An extended operation has to be recognizable and visible for marketing purposes; it needs to acquire a logo and other recognizable features in various domains.

Introduction of strict division of labour to increase productivity in repetitive activities, as specified by early organization theory, has not been confined to industry. With the exponential rise of the size of tasks and staff in HEP laboratories it was expectedly introduced and grew in its importance over time. , For example, the scanning of data was initially done manually, a technique pioneered at the LBL, where a large number of “scanners” were, in fact, highly specialized technicians. (Galison 1990; Swatez 1970; Alvarez 1968) This gradually transformed into the need for specialists in various aspects of the computer analysis of data. The tendency towards specialization became a fact of life with the rise of large particle colliders in the late 1960s; staggering amounts of data were now recorded and processed, and the vastly increased complexity of detectors called for dedicated specialists. Experiments performed on the colliders are much larger and more complex than those on fixed target machines. Even those who say the organization of HEP laboratories is egalitarian admit that the design of detectors bears a resemblance to the factory-like division of labour (Krige 1993, 10). And for a typical experiment, "[a]lthough most members gained some knowledge of systems for which they had no direct responsibility, they typically did not understand the entire detector" (Hoddeson et al 2008, 276). In addition, the colliders are not dismantled for long periods of time, and they service far fewer long-lasting experiments that engage a majority of the researchers and technical staff available (Hoddeson et al. 2008). This necessarily led to the change of tenure requirements at universities, with doctoral degrees awarded for very specialized topics serving the collider needs.

Styles of managing such large research groups varied from one laboratory to another, but they all had to establish hierarchical management of one sort or another. The Lawrence Berkley Laboratory in the 1960s is perhaps the best example of organization managed in accord with classical organization theory; management was firmly in control of each stage of the design, commissioning, data production and analysis, and the laboratory employed a number of highly specialized "scanners" and other specialized staff, who were managed top-town (Krige 1993). The design and commissioning phases, usually taking up a great portion of a mega HEP laboratory's lifetime, were organized as a typical industrial project along the principles of the division of labour in classical organization theory. Often the director of the lab was, in effect, an acting executive. For its part, CERN was run by a distinct management class from the very beginning, for the reasons mentioned above. As part of the ongoing movement towards the division of labour and labour specialization, managers with MBA degrees were introduced into the laboratories in the 1980s (Boisot et. al 2011). Their tasks gradually evolved towards the micromanagement of researchers who work on very specialized tasks in detection and data analysis.

Even as their focus narrowed and became specialized, the research staff working on experiments in large colliders formed a network connecting universities around the world. Just as global expansion required industries to develop a more flexible organizational style, so too the coordination of a diverse matrix combining university affiliates with in-house staff and management required innovative management and communication technologies. Organization became a combination of formal, informal, and patrimonial approaches (discussed in the next section). The most famous response to this requirement was the precursor to the World Wide Web developed at CERN. Mega laboratories also had to establish PR units, design lab logos and other recognizable features as they increasingly turned into social and state mega projects.

State funding agencies have increasingly exerted external pressure on universities and HEP laboratories (Marburger 2015). US laboratories initially had substantial autonomy as the government perceived them as a strategic asset in the Cold War (Greenberg 1970). This virtually free creative period subsided with the economic crisis of the 1970s when oversight became stricter; feedback on performance was gradually introduced and finally formalized in the 1990s. The DOE, the main financing agency of HEP in the US, understood its role as that of a contractor, with universities the supporting units (Marburger 61). Thus, the increased collaboration among universities and their ever-closer interdependence within large HEP projects led to the transfer of many organizational and management functions from academia (Ibid. 61-3).

Finally, the key goal of industry according to classical organization theory should be stability of the product in terms of quality and availability (Peltonen 2016; Taylor 1919). The explicitly set goals (i.e., the research products) of laboratories initially varied across laboratories. Yet as a rule, they were managed in accord with the principles of classical organization theory in their later stages when their size was such that they could not be reassembled into substantially different projects, and accordingly structured their goals This had profound consequence in defining the key epistemic goals of the laboratories. Thus, the management and organization of HEP laboratories akin to the classical organization theory principles as outlined above, defined the epistemic goals in quite broad long-term sense, as facilitating stability of knowledge production.

Thus, the LHC at CERN is organized as an experimental complex to provide a steady stream of diverse experimental results and technological innovations and as a platform for broad educational achievements. (Boisot et al. 2011)[15] More specific tasks (e.g. a search for a specific particle) and their organization (selection of projects, and scientists and staff to pursue them) are assimilated into such a long-term strategy of pursuing broad epistemic goals. Even at the start, CERN took a stability-first approach to mitigate its international complexity; in contrast, US laboratories such as the LBL or SLAC still had the narrow goal-oriented mission of testing a particular hypothesis. Yet with the increase in size the other laboratories established their epistemic goals as a long-term strategy. In fact, there is a general tendency to structure national laboratories in such a way to provide stable outputs in the long term, rather than to organize around short-term tasks. (Hallonsten and Heinze 2012, Westfall 2012)

[15] See also https://home.cern/topics/large-hadron-collider.

3.2 Sociological stream in classical organization theory; bureaucratization of knowledge production in HEP laboratories

Quite early on, the sociological perspective on organization theory pointed to the astronomical increase in the size of institutions as the main incentive for bureaucratization and ensuing symbiosis with the state. The sheer number of organizing tasks made this inevitable. A bureaucratic structure was expected to enable the optimum performance of organizations (both state and industrial) under the pressure of contingencies, such as the increase in size (pertinent in HEP laboratories). Thus, in agreement with classical organization theory, "[b]ureaucratization offers above all the optimum possibility for carrying through the principle of specializing administrative functions according to purely objective considerations" (Weber 1958, 215). Such a structure is open to quantitative efficiency assessments of its goals, that is, assessment of internal efficiency (Ibid.). Technical superiority of bureaucracy over other forms of organizing is the main reason for its imposition. Resources, precision, and speed are optimized thanks to the bureaucratic organization and the professionalization of the class that organizes the institution. A bureaucracy can be contrasted with a collegial organization of work which is less precise, slower, and prone to conflicts. Thus, in general "[t]he larger the organization the more formalized its behaviour. … The more regulating the technical system … the more formalized the operating work and the more bureaucratic the structure of the operating core." (Mintzberg 1989, 338)

Yet Weber points out a downside of this process. The professional inevitably becomes an overly specialized cog in the mechanisms of large institutions, be they industrial or scientific. This gives rise to another set of negative effects in large bureaucratized institutions. For one thing, the work atmosphere changes; "normal bureaucracy" providing optimal organization turns into “pathological bureaucracy”. Weber was one of the first, if not first, to recognize the inevitability of the tendency towards bureaucratization in scientific institutions in the business of knowledge production and what he recognized as its emerging downside:

> In the field of scientific research and instruction, the bureaucratization of the always existing research institutes of the universities is a function of the increasing demand for material means of management. Liebig’s laboratory at Giessen University was the first example of big enterprise in this field. Through the concentration of such means in the hands of the privileged head of the institute, the mass of researchers and docents are separated from their means of production in the same way as capitalist enterprise has separated workers from theirs. (Weber 1958, 225)

As the size of the HEP laboratories increased administrating funds, human resources, engineering projects, facilities, public relations, and other segments of such large institutions have been delegated to professionals in those areas, or to formally educated physicists who spend their careers in managing and specializing in similar tasks. In fact, departments for experimental and theoretical physics in the laboratories are only two of many specialized departments. The physicists’ work is often supervised by multiple supervisors affiliated with various projects, where the tasks they delegate to the physicists are structured in project- related collaboration across departments. It is not unusual for physicist to have their work managed by multiple supervisors affiliated with different departments.

As pointed out earlier, HEP laboratories feature an informal, patrimonial bureaucracy (Boisot et al. 2011, Ch. 11). Many or most of the participants in projects are affiliated with universities around the world, not with the laboratory *per se*. This makes establishing a formal hierarchical structure impossible, even one resembling a structure from the university setting. The hierarchy is not based on a legal but on an informal, largely unregulated, web of power.

Moreover, there is a struggle between two types of hierarchy, a formal one coming from the state and industry and an informal one emerging from the university affiliated participants who derive their professional standing from the university setting. The two systems jostle for position in mega laboratories, with negative consequences all round. Despite their dramatic and desperate tone, the following two passages clearly list the downsides:

> The enormous size of Big Science projects requires constant oversight by administrative bodies…. The true risk is excessive bureaucratization of large scientific projects. Public authorities, which have the fair duty of monitoring the expenses incurred by large projects, can impose decisions based on purely financial considerations, neglecting their scientific and technical aspects. Administrators are accustomed to operate quite different than scientists, and can even inadvertently destroy the special vitality that thrives in a research environment. (Guidice 2012)

> The sheer size of the undertaking, the micromanagement by DOE, and the intensity and frequency of external oversight all led to a bureaucratic internal culture at the laboratory. In the name of cost control, technically needed changes and design trade-offs were discouraged. Decisions on technical alternatives were distorted by "political acceptability" and were at times made late or not at all… Key scientific and technical people were generally placed low in the decision chain. (Panofsky et al., 1994)

In any event, the administration of the laboratories has varied widely, from mechanistic bureaucracy to flexible and patrimonial. As noted previously, CERN was organized top down to reconcile the multiple national interests of those participating in the project (Hermann et al. 1987). This inevitably led to a more complex hierarchical organization. But the negative effects of such bureaucracy appeared fairly quickly, with experimenters complaining about the "Barons of CERN" (Ibid.) who imposed tasks on them. When there is coordination across institutions, a patrimonial, informal, model of administrating becomes necessary, as the management does not have formal administrative levers to impose tasks on the external collaborators who are affiliated with various universities and institutes. This patrimonial structure is, unsurprisingly, quite similar to the collaboration within multinational corporations working on a single project and embodies the matrix organizational structure (Boisot et al. 2011, Chompalov et al. 2002, 765). While the administration is informal, the organizational structure controlling research, data, and publication of results becomes informal but tight. Moreover, in knowledge-intensive institutions in general the formal organizational structure tends to loosen up due to fairly dynamic and unpredictable nature of the tasks and focused expertise of most employees that cannot be supervised directly as supervisors lack detailed knowledge of the process. (Von Nordenflycht 2010, Ditillo 2004, Karreman and Alvesson 2004) Thus patrimonial and informal organizational structure arises. The loosinening of the organizational and managerial structure in such context may not be unavoidable and may be even their downside and result in decrease of their efficiency. (Alvesson and Svenigsson 2003) In any case, this trend is certainly not a unique feature of HEP laboratories.

Finally, the flattening of economic and social differences is unavoidable in centralized bureaucratized institutions. (Weber 1958) Mintzberg (1989, 338) summarizes this tendency:

> "The more complex the technical system, the more elaborate administrative structure, especially the larger and more professional the support staff , the greater the selective

decentralization (to that staff), and the greater the use of liaison devices to co-ordinate the work of that staff. Essentially, if an organization is to use complex machinery, it must hire staff experts who can understand that machinery - who have the capability to design, select, and modify it. And then it must give them considerable power to make decisions concerning that machinery, and encourage them to use the liaison devices to ensure mutual adjustment among them."

This is true of HEP laboratories as well. The equalization of authorships in knowledge production and catering to tenure are marks of this tendency. As we have pointed out earlier, many authors have focused on this egalitarian aspect in their studies of the organization in HEP laboratories in order to hail their supposed organizational uniqness. Yet this feature of organization is not an exceptional occurrence in any large institution; it is a complex epiphenomenon of bureaucratized institutions and thus should not be emphasized as a unique and necessarily epistemically beneficial feature of HEP laboratories.

A positive take on exponential growth has been articulated as the economy of scale (see e.g. Brinkman and Leslie 1986): centralizing production ultimately decreases the logistic costs. Another argument in favour of such an approach is that the mega institutions are a kind of environment that gathers human and financial resources around goals that could not be pursued without such mega institutions. In the case of HEP laboratories, the expectation has been that "this produces very fertile ground that is naturally open to innovation well beyond the planned objectives of the project" (Giudice 2012, 110). Some empirical research, however, suggests the opposite is true: innovation is eventually stifled by over-centralizing (Agrell and Gustafson 1996) and various atmospheric effects of gathering large numbers of scientists into a single project or a tightly knit set of projects result in a variety of crippling effects (Torrisi 2014). An early warning of this came from A. Weinberg (1962, 255), who also pointed out that the internationalizing of laboratories acts as a counter balance to this negative effect as it stabilizes funding for political reasons. The multinational nature of large expensive scientific projects works in their favour: “[t]he International Space Station was estimated to cost more than three times that of the LHC, its cost was continually rising and the scientific motivations for its construction were rather weak. The international element and prior agreements with foreign countries certainly worked in [its] favor” (Guidice 2012, 103).

The tremendous, often multinational, investments in mega laboratories quickly turned them into institutions that were too big to fail; “Colliding beams detectors are so large and costly that no one even thinks of dismantling them at the end of the run; the experiments are effectively unending” (Hoddeson et al. 2008, 281). They become social projects and a scientific activity in which the entire society was engaged one way or another and, thus, virtually impossible to dismantle. It inevitably defines its epistemic goals in broad terms, as pointed out earler. Yet bureaucratization and its hierarchy often go hand in hand with the centralization of funding. Large industrial projects and military organizations alike required such centralization in the first half of the 20th century, with the government-funded Manhattan project a case in point. The change in the attitude of the state as the funder of HEP laboratories was a result of a rather usual developmental trajectory of the over-sized institutions, identified by Weber early on. The costs paid for from the funds borrowed from the public will rise tremendously in the case of big centralized organizations even if their productivity is constantly improving (i.e. if they are well organized). The industrial projects that grow fast are inevitably, at least partially entrusted to the state for financial reasons. This financial help can be beneficial for the execution of the project when vast funds are needed, but the state eventually assimilates the project’s organizational as well as financial scheme into the state bureaucracy as it seeks accountability as the major funder. Thus, in the case of HEP laboratories, initially "society was willing to buy… argument, up to a point, that good science is the bottom line and that the legalistic mechanisms of accountability being implemented elsewhere were an expensive luxury whose marginal benefit to society could not balance the reduction in scientific output necessary to create it" (Marburger 2015, 78). In other words, the physicists were allowed to organize their laboratories on their own even though the state was the funder. The development of the laboratories in the US during and a few decades after the WWII was predicated on a belief of the state agencies as the funders that explicit justification of the organizational scheme of the laboratories was not required as the scientists knew best how to do it. Yet eventually there was a change in the attitude of the state as the funder, a result of the funding trajectory identified by Weber.

As Weber (1958) points out, an increase in bureaucracy and secrecy eventually go hand in hand. Barring exceptions of security services, the goals and methods of publically funded institutions should be public. Yet obstacles to this eventually emerge in mega laboratories. For example, traditional peer review is not possible; it becomes an internal process as almost all the scientists working in the field are engaged in the project. It is a phenomenon identifiable across professional institutions Van Nordenflycht (2010) labels 'opaque quality' of services. In addition, the highly specialized science does not help the wide dissemination of results; publications of discoveries are simply short summaries with little content, while all the relevant publications are internal. There is also a default resistance to external critique; the presumption that it will be suspicious is almost inevitable, since all the acknowledged experts are working on the mega lab's project. This contrasts to the traditional culture of universities and can have negative epistemic consequences.

3.3 Cultural modern organization theory; focus on informal and decentralized organization in HEP

In his work on organization theory, Merton (1940) focused on organizations as social systems. He advocated the view that informal characteristics of organizations are far more important than the transparent and deliberately introduced formal "facade" (Merton 1940). Thus, the analysis of an organization ought to focus on the relationship between individual and organization, as the status of the individual and the positive culture of the institution are more important to productivity than is an imposed top-down organizational structure. Normatively speaking, it is far more effective if managers are embedded in the community of specialized workers, mediating between them and the goals, rather than top-down micromanaging as a removed class. In what became known as cultural modern organization theory, Merton and others argued that the work atmosphere plays a decisive role in increasing the productivity, even though it is an informal aspect of organization. The human and social characteristics of the organization are primary movers of the organization, and informal cliques are more important than the transparent structure and division of labour. If this is indeed the case, applying the rules of classical organization theory in a mega laboratory context can be harmful, as it stifles or even dissolves informal community.

A comprehensive multi-year study in Hawthorn factory was conducted to test outcomes in productivity of various organizational structures, and primarily, social composition, formal and informal, of teams. (Rothlisberger and Dickson 1964) The data on the movement and productivity of workers, automatically recorded demonstrated that flat and lose management structures were substantially more productive. The organizational adjustment should not be confined to the social composition and culture of people in it, but should extend to the wider economic environment, and especially, a wider community and its social and cultural composition. The early case studies of a regional development in Tennessee (Selznick 1949) and a gypsum plant (Gouldner 1954) assessed the latter kind of adjustment and its results. The case studies, discussions, and analysis focusing on the "climate" or "atmosphere" in organizations (Blake and Mouton 1964) has evolved into research addressing the so-called "organizational cultures" in the late 1970s. (Hoffstede et al. 1990, Pettigrew 1979) Another line of research looks at the role broader environment plays in managing organizations. (Nystrom and Starbuck 1981)

Fermilab's first director R.R. Wilson organized the first major US national laboratory in the early 1970s by deliberately placing individual scientists and their needs at the centre, in contrast to the formal, hierarchical and closely-knit organization of the in-house specialists at LBL and CERN, which makes his management style exemplary of cultural modern organization theory. He was not alone in this thinking; as we have mentioned earlier other prominent figures in the physics community reacted to what they perceived as the increasingly industrial organization of the research process in particle laboratories, and the factory-like conditions that undermined creativity. They objected to seeing physics going down the road of industrial organization as conceived by classical organization theory. Some left the field altogether to pursue small scale research in biology, but Wilson stayed and built an alternative vision at

Fermilab: “He expressed his vision of research as performed ideally by lone, independent scientists … Hoping to redeem what the Manhattan Project had wrought upon the world, Wilson … planned a utopian laboratory intended as a place of beauty… and contributing to cultural and social advancement” (Hoddeson et al. 2008, 6).

Under Wilson’s directorship, the laboratory was a place for assembling experiments by outside groups, not a centralized in-house run institution (Hoddeson et al. 2008). Moreover, the in-house physicists were assigned administrative work to prevent them from gaining too much power in performing experiments (Traweek 2009, 137; Hoddeson et al. 2008). The dependence on external groups led to the management to oversee the budget and tightly schedule activities (Marburger 2015, 54), unlike the centralized laboratories that vastly over-spent often just because they could and lowered their financial expectations to have their proposals accepted.

Wilson’s vision within the HEP context called for the removal of the rigid hierarchy, a focus on individual intellectual and other needs of scientists, and the introduction of an informal structure of administrating the laboratory and experiments. Yet eventually the lab was beaten by CERN in a few break-through discoveries; this resulted in a major organizational overhaul that led to centralization and the establishment of long-lasting in-house experimental groups.

The factor of “work atmosphere” played a key role in organizational change as well.[16] In the 1970s and 1980s, the main issue in the debate among physicists on “the best environment for physicists” (Traweek 2009, 126) centred on the relations between in-house and outside groups (Traweek 2009; Hoddeson 2008). This was not surprising, as the “[r]elations among the groups [were] highly, though informally, structured” (Traweek 2008, 127). The in-house groups were

[16] The cultural modern approach to organization has ongoing relevance, with policy analysts in industry and science seeking to explain variations in the efficiency of institutions. This sort of research is rare in its explicit connection of organization theory and organization in science; it is on the right track and stands to shed useful analytical light on the HEP laboratories.

typically long-lasting and closely-knit, but they also had to work with groups from outside. The formal and informal relationships between the in-house and outside research groups became the crucial organizational point. The physicists themselves often perceived failures to compete with other labs, or the fact they missed discoveries that technically could have been made at their lab but instead were made at another one, as stemming from a type of organization that favoured outside groups (Ibid. 130). The in-house groups at SLAC emphasized their technical superiority over outside groups (Ibid. 128), and the lab director ultimately re-established the "lab's traditional decision-making structure" (Ibid. 129).

The epistemic goal behind the organization of such laboratories was not defined in terms of immediate product – i.e. results of specific tests of a chosen set of hypothesis. Such short-term tasks were delegated to a wider community of external research groups hosted in the laboratory, and their way of organizing in order to achieve them. Instead, the epistemic goal was focused on facilitating a flexible structure for explorative searches that were exected to bear cutting edge results.

Barnard's cooperative theory (Barnard 1938) is another instance of the cultural modern organization theory. It addresses "non-logical" thinking, or pragmatic thinking under pressure. In fact, the pragmatic, rather than the principle-based reasoning formalized in either decision theory or theory of rational choice, may be crucial in decision making in HEP laboratories (Staley and Rehg 2008). If so, formal decision theory cannot be a major guide to organizing an institution, a view held by the proponents of the rational modern approach (discussed in the next section). Nor is transparent formal organization the reason for the stability of the production process. We ought to focus on building the common goals, ideology, and culture of the organization, not on providing direct financial or career-success incentives. This may be true of HEP labs as well;

according to Corley et al. (2006), in physical sciences "[m]ethodological or epistemic norms within a discipline often define the 'rules' that the discipline uses to deal with a variety of work-related issues," while "the cultural status of the discipline is entangled in the shared epistemology between the members of the discipline" (p. 977).

3.4 Rational modern organization theory; formal streamlining of knowledge production process in HEP

The operational analysis of rational systems and choices resulted from the military need for efficient rational management systems and decision-making in WWII. (Hoddeson 1993; Edwards 1997; Johnson 1997) Mathematical modelling, simulations, and quantitative optimization were developed to address these needs in quantifiable, transparent and applicable ways. The methods were meant to be applied widely in industry after the war.

The symbiosis with the systems theory of Bertalanffy and others resulted in a rational-scientific epistemology of organization (Peltonen 2016, 91) whose goals include the identification of operating principles and their optimization, as well as optimal decision-making procedures of individuals. Beer (1959) developed a thorough theoretical account of "a cybernetic factory" based on a set of computational principles. H. Simon's decision-making theory (Simon 1947) detached operational analysis from qualitative studies by Weber and other sociologists by focusing on models of operations that identify and analyze relevant variables. This gradually resulted in the separation of the sociological study of organization from MBA studies. The onus in the latter work is on optimizing hierarchical, vertical structures in order to break the hierarchical bureaucracy. Rationality is treated as bounded, within the operational framework of the organization. Thus, prioritizing and evaluation, that is, considerations of consequences, are always part of operations. For instance, various predictions, contingencies such as power of technology or size of the operation, or politics of funding are taken into account during the planning phase. The approach has been developed further as computational organization theory. (Carley and Wallace 2001)

This approach became a feature of the planning and organization of HEP labs. In this, they were building on the experience of early organizers of the Manhattan project and organization of Los Alamos Laboratory in particular (Hoddeson 1993), and notably their discovery that linking military organization and science benefited from these methods. Anticipation of technological advances and estimations of the capacity of the existing and planned technology have always driven decisions on the long-term development of HEP laboratories; for example, the development of the Large Hadron Collider instead of the lepton linear collider was largely predicated on such estimates. And in accord with the rational modern approach, laboratories also introduced quite early on an operational self-assessment in the form of citation metrics based on the INSPIRE archive of HEP papers. Simulations and modelling have been part of the scientific process in HEP laboratories since the beginning. The laboratories were on the leading edge of the development and use of such techniques. Yet these techniques have only recently been used to assess the capacity of various organizational structures in scientific institutions (Perović et al 2015; Zollman 2007). (The last section returns to this issue.) In any case, there is a clear epistemological goal of assessing and accordingly optimizing organizations from this point of view. The organization is formalized network of nodes and their relations and the assessments of the scientific network are implemented top-down in order to optimize the network’s operation, given its desired product, either wider knowledge-production or narrow hypothesis testing.

3.5 Structural contingency organization theory; the size matters in organizing HEP

The structure of each unit and technology implemented in the production process requires a specific, usually hierarchical, division of labour, and situational contingencies such as the size of the organization or the phase of its development inevitably frame the organizational structure. The goal of organizational analysis, according to structural contingency theory (Thompson 1967; Woodward 1958), is to find an optimal form of organization by assessing operating methods with respect to these contingencies. This represents a shift from the study of general organizational systems to the study of the internal contingent organizational structure. A range of different types of organizations can be included, from bureaucratized hierarchical organizations to flexible organic organizations, as can a range of contingency factors, from size, to technology, environment, and business strategy (Peltonen 2016, 116). The treatment of each contingency has to be contextualized, measured against many other factors – and each can benefit or harm the organization depending on the context.

Thus, for instance, an increase in the size of an institution will generally lead to a substantial increase in bureaucratization. Early empirical studies from the Aston school (Pugh et al. 1968), as well as more recent studies (Wang et al. 2015) demonstrate that an increase in size also leads to increased specialization and structural diversification. (Blau 1970; Peltonen 2016, 120) In fact, this issue is central to understanding the organizational challenges faced by HEP laboratories. The downside of increasing the size of research institutions across sciences, including physics, has been analyzed using a number of parameters (Carillo et al. 2013; Von Tunzelman et al. 2003; Katz 1982). The results show that the initial advantages of size eventually bring about diminishing returns, so the ways of restructuring laboratories and their priorities in the research process are crucial. The question is to what extent this applies to the HEP laboratories and how.

The focus on building a favourable local context rather establishing a coherent general system of organization may be another essential component of the organizational development of HEP laboratories. Japan and the US have developed different models: Japan's model is that of a household where mutual agreement is key, while US labs are tightly managed top-down, much like sports teams (Traweek 2009, 149). As is generally acknowledged, the Japanese industrial management practices based on the "household" turned out to be superior to the US model in the car industry. Japanese factories were strategized around properly timing multiple autonomous and the level-field partnerships. Given the failure of the US model in the auto industry, some questioned its ability to manage big laboratories (Marburger 2015, 50)

Instead of full-blown assessment and optimization of the network, akin to Beer's "cybernetic factory", optimziation of the network in this case aims at identifying the limits of its key contingencies, e.g. size/efficiency relation. Whatever the actual goal in terms of knowledge production (broad or narrow, long or short term) the contingency will affect it and thus understanding its limits is crucial.

4. Organization of HEP laboratories: their epistemic utility and performance

4.1 Why it is important to measure performance of HEP laboratories

The US government gradually introduced accountability, along with substantial penalties for infractions, into large scientific projects, including large colliders (Marburger 2015, 53-54). In fact, this was the basis for the cancellation of the SSC funding. In Europe, this type of oversight was present from the very beginning, and CERN developed in a different social and political context than the US mega laboratories. The US trend towards close oversight emerged after the end of the Cold War. Although the funding agencies (i.e. government) began to request feedback on the performance of the laboratories, the HEP communities and policy makers did not make a concerted effort to define their goals and the corresponding metrics. Of course, a major obstacle to performance analysis in science is that advocacy, rather than thoughtful policy, usually leads funding decisions, but efficiency metrics are the basic level of any science policy: funders, policy makers, and often scientists themselves require them.[17]

4.2 Organization theory, epistemic utility and efficiency

Epistemic utility, broadly conceived, includes various forms of knowledge produced by scientific institutions such as the HEP mega laboratories. The goal of measurement is to identify the adequacy of an organizational structure and its various aspects as defined by different strands of organization theory, with respect to a particular kind of epistemic utility and to identify the trade-offs this implies. For example, how does the size of a laboratory affect the production of experimental results?

In the case of HEP laboratories, an organization's epistemic utility, i.e., its ability to meet its knowledge production goals, can be assessed quantitatively or qualitatively, that is, along the lines of either rational modern or cultural modern organization theory. Now, we can divide these goals into narrow and broad ones. Narrow goals of knowledge production are set by the

[17] As we have mentioned earlier, an important epistemic trait of big science generally and big physics in particular is the danger of diminishing returns due to a lack of diversity of research goals and methods. This must be addressed when constructing the performance criteria of mega laboratories, as must their size.

researchers working on an experiment and concern the production of experimental results. These narrow scientific hypothesis-driven goals can be analyzed through the lens of rational modern organization theory. Any research method has an internal measure of its efficacy. The self-assessment of productivity through the comprehensive HEP archive of papers and citations Inspire established and run by the HEP community (mentioned above) is a good model for measurements of this sort and can be applied across other scientific fields.

In contrast, classical organization theory focuses on the stable continuous production of results, not on narrow short-term goals. In terms of knowledge-intensive institutions, then, one should aim to build a balanced organization offering a continuous stream of relevant knowledge, not an organization performing well to meet a short-term demand. CERN is managed as a continually updating and evolving stable long-term operation aiming to satisfy a number of broadly defined goals. Performance defined in this way focuses, broadly speaking, on a comprehensively satisfying use of large public funds. In fact, all large colliders should be assessed against such broader considerations.

One such broad consideration is the usefulness of experimental results to other similar enterprises and other scientific fields. Another is that the laboratory can be expected to provide a constant output of innovative technologies. And it is a place where a generation of physicists is educated, thereby providing a platform for their success in university careers and their achievements of teaching goals. These broader criteria are harder to quantify, and the analysis must rely, at least in part, on qualitative assessments of the larger social and cultural context of the laboratory.

Now, in terms of identifying the relevant features of the structure of the organization, the organization can be assessed as a transparent administrative structure, following classical organization theory, focusing on the intricate division of labour, the role of the management class and its relationship with the research and technical staff. Following cultural modern theory, however, the work atmosphere and informal groups are equally essential to well-organized operation ( ). Finally, various contingency factors, especially the size of the laboratory, not to mention the administrative structure in its various forms, are main considerations identified by structural contingency and sociological theory, respectively.

How effectively can the efficiency of each of these aspects of the organization identified with respect to the production of narrow and broader goals be tested quantitatively and qualitatively? Can a comprehensive analysis even be put together? Computer simulations, decision theoretic analysis, assessments based on scientometric criteria, and certain sociological and anthropological methods can measure the effectiveness of various aspects of the organizational structures in terms of the efficacy of achieving both narrow and broader goals. These existing methods should be comprehensively applied and developed. The perception of the role of various organizational factors in the performance of the laboratory by researchers or policy-makers themselves can also be tested and concrete solutions offered.[18]

References:

Agrell, A. and Gustafson, R., 1996. Innovation and creativity in work groups. *Handbook of work group psychology*, pp.317-343.

Alvarez, L.W., 1968. Recent developments in particle physics. *Evolution of Particle Physics. A Volume Dedicated to Edoardo Amaldi in his Sixtieth Birthday*, pp.1-49.

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Alvesson, M. and Sveningsson, S., 2003. Good visions, bad micro-management and ugly ambiguity: contradictions of (non-) leadership in a knowledge-intensive organization. *Organization Studies*, *24*(6), pp.961-988.

Brinkman, P.T. and Leslie, L.L., 1986. Economies of scale in higher education: Sixty years of research. *The Review of Higher Education*, *10*(1), p.1.

Beer, S., 1959. *Cybernetics and management.* London: English University Press.

Blau, P.M., 1970. A formal theory of differentiation in organizations. *American sociological review*, pp.201-218.

Blake, R.R. and Mouton, J.S., 1964. *The new managerial grid: strategic new insights into a proven system for increasing organization productivity and individual effectiveness, plus a revealing examination of how your managerial style can affect your mental and physical health*. Gulf Pub. Co..

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

Carillo, M.R., Papagni, E. and Sapio, A., 2013. Do collaborations enhance the high-quality output of scientific institutions? Evidence from the Italian Research Assessment Exercise. *The Journal of Socio-Economics*, *47*, pp.25-36.

Carley, K.M. and Wallace, W.A., 2001. Computational organization theory. In *Encyclopedia of Operations Research and Management Science* (pp. 126-132). Springer US.

Chester, B., 1938. The functions of the executive. *Harvard University Presse, Cambridge*.

Cetina, K.K., 1999. *Epistemic cultures: How the sciences make knowledge*. Harvard University Press.

Chompalov, I., Genuth, J. and Shrum, W., 2002. The organization of scientific collaborations. *Research Policy*, *31*(5), pp.749-767.

Cohen, Y., 2003. Fayol, un instituteur de l'ordre industriel. *Entreprises et histoire*, (3), pp.29-67.

Corley, E.A., Boardman, P.C. and Bozeman, B., 2006. Design and the management of multi-institutional research collaborations: Theoretical implications from two case studies. *Research policy*, *35*(7), pp.975-993.

Ditillo, A., 2004. Dealing with uncertainty in knowledge-intensive firms: the role of management control systems as knowledge integration mechanisms. *Accounting, Organizations and Society*, *29*(3), pp.401-421.

Edwards, P.N., 1997. *The closed world: Computers and the politics of discourse in Cold War America*. MIT Press.Fayol, H., 1949. *General and industrial management*. London: Pitman.

Galison, P., 1985. Bubble chambers and the experimental workplace. *Observation, experiment, and hypothesis in modern physical science*, *2*, pp.97-112.

Galison, P. and Hevly, B.W., 1992. *Big science: The growth of large-scale research*. Stanford University Press.

Gantt, H.L., 1974. Work, Wages and Profit The Engineering Magazine, New York, 1910; republished as Work, Wages and Profits, Easton, Pennsylvania.

Giudice, G.F., 2012. Big Science and the Large Hadron Collider. *Physics in Perspective*, *14*(1), pp.95-112. (Gudice G.F. 2011, CERN-PH-TH/2011-288)

Gouldner, A.W., 1954. Patterns of industrial bureaucracy,Glencoe, IL: Free Press.

Greenberg, D.S., 1970. *The Politics of Pure Science: An Inquiry Into the Relationship Between Science and Government in the United States*. New American Library.

Hallonsten, O. and Heinze, T., 2012. Institutional persistence through gradual organizational adaptation: Analysis of national laboratories in the USA and Germany. *Science and Public Policy*, *39*(4), pp.450-463.

Hermann, A., Krige, J., Mersits, U., Pestre, D. and Belloni, L., 1987. *History of CERN.* North Holland.

Hoddeson, L., 1993. *Critical assembly: a technical history of Los Alamos during the Oppenheimer years, 1943-1945*. Cambridge University Press.

Hoddeson, L., Kolb, A.W. and Westfall, C., 2008. *Fermilab: Physics, the frontier, and megascience*. University of Chicago Press.

Hofstede, G., Neuijen, B., Ohayv, D.D. and Sanders, G., 1990. Measuring organizational cultures: A qualitative and quantitative study across twenty cases. *Administrative science quarterly*, pp.286-316.

Johnson, S.B., 1997. Three approaches to big technology: Operations research, systems engineering, and project management. *Technology and Culture*, *38*(4), pp.891-919.

Kärreman, D. and Alvesson, M., 2004. Cages in tandem: Management control, social identity, and identification in a knowledge-intensive firm. *Organization*, *11*(1), pp.149-175.

Katz, R., 1982. The effects of group longevity on project communication and performance. *Administrative science quarterly*, pp.81-104.

Kragh, H., 2002. *Quantum generations: A history of physics in the twentieth century*. Princeton University Press.

Krige, J., 1993. Some socio-historical aspects of multinational collaborations in high-energy physics at CERN between 1975 and 1985. In *Denationalizing science* (pp. 233-262). Springer Netherlands.

Marburger III, J.H., 2015. *Science policy up close*. Harvard University Press.

Martin, B.R. and Irvine, J., 1984a. CERN: Past performance and future prospects: I. CERN's position in world high-energy physics. *Research Policy*, *13*(4), pp.183-210.

Martin, B.R. and Irvine, J., 1984b. CERN: Past performance and future prospects: II. The scientific performance of the CERN accelerators. *Research Policy*, *13*(5), pp.247-284.

Martin, B.R. and Irvine, J., 1985. Basic research in the East and West: A comparison of the scientific performance of high-energy physics accelerators. *Social Studies of Science*, *15*(2), pp.293-341.

Maruyama, K., Shimizu, H., and Nirei, M., 2015. Management of science, serendipity, and research performance: Evidence from scientists' survey in the US and Japan. *Research Policy* (44), pp. 862-873.

Merton, R.K., 1940. Bureaucratic structure and personality. *Social forces*, pp.560-568.

Mintzberg, H., 1989. The structuring of organizations. In *Readings in Strategic Management* (pp. 322-352). Macmillan Education UK.

Nystrom, P. C. & Starbuck, W. H. (Eds.), 1981. Handbook of organizational design: Adapting organizations to their environments. Oxford: Oxford University Press.

Kragh, H., 2002. *Quantum generations: A history of physics in the twentieth century*. Princeton University Press.

Panofsky, W.K., Pewitt, D., Nygren, D.R., Ramond, P., Reiland, R.J., Carone, C. and Roy, R., 1994. The SSC's End: What Happened? and What Now?. *Physics Today*, *47*(3), pp.13-92.

Peltonen, T., 2016. *Organization Theory: Critical and Philosophical Engagements*. Emerald Group Publishing.

Perović, S., Radovanović, S., Sikimić, V. and Berber, A., 2016. Optimal research team composition: data envelopment analysis of Fermilab experiments. *Scientometrics*, *108*(1), pp.83-111.

Pettigrew, A.M., 1979. On studying organizational cultures. *Administrative science quarterly*, *24*(4), pp.570-581.

Pugh, D.S., Hickson, D.J., Hinings, C.R. and Turner, C., 1969. The context of organization structures. *Administrative science quarterly*, pp.91-114.

Roethlisberger, F.J. and Dickson, W.J., 1964. *Management and the worker: an account of a research program conducted by the Western Electric Company, Hawthorne Works, Chicago, by FJ Roethlisberger and William J. Dickson, with the assistance and collaboration of Harold A. Wright*. Harvard Univ. Press.

Riordan, M., Hoddeson, L. and Kolb, A.W., 2015. *Tunnel Visions: The Rise and Fall of the Superconducting Super Collider*. University of Chicago Press.

Selznick, P., 1949. *TVA and the grass roots: A study in the sociology of formal organization* (Vol. 3). Univ of California Press.

Simon, H.A., 1947. Administrative behavior, a story of decision processes in business organization. *London, Macmillan (1951)*.

Staley K. and Rehg, W., 2008. The CDF collaboration and argumentation theory: The role of process in objective knowledge. *Perspectives on science, 16*(1), pp.1-25

Swatez, G.M., 1970. The social organisation of a university laboratory. *Minerva*, *8*(1), pp.36-58.

Taylor, F.W., 1919. *The principles of scientific management*. Harper & brothers.

Thompson, J.D., 1967. *Organizations in action: Social science bases of administrative theory*. Transaction publishers.

Torrisi, B., 2014. A multidimensional approach to academic productivity. *Scientometrics*, *99*(3), pp.755-783.

Traweek, S., 2009. *Beamtimes and lifetimes*. Harvard University Press.

Von Nordenflycht, A., 2010. What is a professional service firm? Toward a theory and taxonomy of knowledge-intensive firms. *Academy of management Review*, *35*(1), pp.155-174.

Von Tunzelmann, N., Ranga, M., Martin, B. and Geuna, A., 2003. The effects of size on research performance: A SPRU review. *Report prepared for the Office of Science and Technology, Department of Trade and Industry*.

Wang, J., Thijs, B., & Glanzel, W., 2015. Interdisciplinarity and impact: Distinct effects of variety, balance, and disparity. PLoS One, 10(5), e0127298.

Weber, M., 1958. *From Max Weber: Essays in sociology. Translated, edited and with an introduction by HH Gerth and C. Wright Mills*. Kegan Paul.

Weinberg, A.M., 1963. Criteria for scientific choice. *Minerva*, *1*(2), pp.159-171.

Westfall, C., 2012. Institutional persistence and the material transformation of the US national labs: The curious story of the advent of the Advanced Photon Source. *Science and Public Policy*, *39*(4), pp.439-449.

Woodward, J., 1958. Management and technology (Problems of progress in industry series, No. 3). *Her Majesty's Stationery Office, London*.

Wrege, C.D. and Perroni, A.G., 1974. Taylor's pig-tale: A historical analysis of Frederick W. Taylor's pig-iron experiments. *Academy of Management Journal*, *17*(1), pp.6-27.

Zollman, K.J., 2007. The communication structure of epistemic communities. *Philosophy of science*, *74*(5), pp.574-587.