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The Limitations of the Conceptual Framework of the Heterogeneous Engineer for Leadership in Megascience Projects

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The limitations of the conceptual framework of the heterogeneous engineer for leadership in megascience projects

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Abstract

The concept of the 'heterogeneous engineer', devised by Krige (2001) offers the intriguing possibility of applying a concept devised in the history of science literature to the academic study of leadership. This study sought to use the heterogeneous engineer as a conceptual framework to develop wider leadership theory. Two case studies were selected – the Tevatron at Fermilab in the United States and the Large Hadron Collider (LHC) at CERN on the Franco-Swiss border. The LHC was of particular interest because Carlo Rubbia, identified by Krige (2001) as a classic heterogeneous engineer, played a leading role in its conception. However, the results of this study indicate that Carlo Rubbia is a relative anomaly within the context of scientific leadership and therefore the heterogeneous engineer is an inappropriate construct for the development of wider leadership theory. The paper also identifies and describes the generalised characteristics of leaders in megascience projects as a starting point for future work in this field.

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Keywords

Megaprojects, big science, leadership, project management, research infrastructure

Introduction

This paper seeks to identify the limitations of the heterogeneous engineer concept by drawing on data from a study of two megascience projects – the Large Hadron Collider (LHC) and the Tevatron. The work of Krige (2001) appears to be highly useful as a conceptual framework for understanding the nature of leadership in scientific collaborations and other high technology projects. A 'heterogeneous engineer' is considered to be an individual capable of mobilising the human, financial, and scientific resources necessary to secure successful project outcomes (Krige, 2001). This conceptual framework is effectively a personified version of 'heterogeneous engineering', a social means for understanding technical change (Law, 1987b). Krige (2001) cited a single individual, Carlo Rubbia, as a heterogeneous engineer based on his role in the discovery of the W and Z bosons at the UA1 detector at the European Organisation for Nuclear Research (CERN)[1]. This concept shares certain attributes with other leadership concepts, notably the systems builder from the large technical systems literature which will also be discussed in the literature review (Hughes, 1987).

Megascience projects are a subcategory of the megaprojects literature that incorporate the additional characteristics of a high or 'super high' level of technological uncertainty (Eggleton, 2017). The LHC at CERN in the Franco-Swiss border region might be considered an exemplar megascience project that incorporates both the financial scale of megaprojects in its 5.8 billion Swiss Francs (CHF) budget[2] and the high level of technological uncertainty associated with its magnetic and cryogenic systems (Evans, 2009, 2014). Its conception as the next 'big machine' at CERN occurred during the Director-Generalship of Carlo Rubbia, who Krige (2001) identified as a heterogeneous engineer. These twin factors provided the opportunity to use an LHC leadership case study to develop the heterogeneous engineer beyond Rubbia and create broader understandings of leadership. Other megascience projects include the Tevatron at Fermilab, the Space Shuttle, and the cancelled Superconducting Super Collider (Shenhar, 1993; Hoddeson *et al.*, 2008; Riordan *et al.*, 2015). The discussion of the principal characteristics of megascience projects is in the megascience projects section, namely the financial scale and the significant levels of technological uncertainty. One particular quirk relating to megascience projects is that project managers are generally trained from within the scientific discipline rather than using professional managers with no scientific background (Smith, 2007; Hoddeson *et al.*, 2008; Evans, 2014). This factor is becoming an area of significant policy interest, with work currently being undertaken to understand and attempt to standardise

[1] It must be noted that the acronym CERN is derived from the title for the provisional council setup to organise the laboratory in the 1950s and remained the acronym for the laboratory as a whole even after the provisional council dissolved.

[2] Approximately $US5.9 billion based on exchange rates in June 2018 $*0.9897/CHF*

management training across different types of research infrastructures (Paterson *et al.*, 2017). This paper therefore supports these efforts by informing the conceptual agenda that underpins the training.

The Tevatron at Fermi National Accelerator Laboratory in particular, where Rubbia also conducted experiments, was an accelerator in the United States that first began operation in 1983 and enabled several new discoveries, most notably the top quark in 1995 (Collaboration *et al.*, 1995; Hoddeson *et al.*, 2008). It was closed after the commissioning of the LHC in 2011 (Riordan, Hoddeson and Kolb, 2015). The inclusion of a Tevatron case study offered the additional opportunity to identify what leadership behaviours were unique to a single project context and what is more generalisable.

Two case studies were developed examining leadership in the cases of the Tevatron at Fermilab and the LHC at CERN, both of which meet both the financial and technological uncertainty criteria necessary to be considered megascience projects. As the LHC was still in operation during the fieldwork, it offered the opportunity to interview leaders associated with experimental collaborations, primarily Compact Muon Solenoid (CMS) and A Toroidal LHC ApparatuS (ATLAS) experiments. As Rubbia was an experimentalist who moved into laboratory management temporarily before returning to experimentation, it was perfectly feasible that Rubbia was an exemplar experimentalist rather than a leader within accelerator construction.

The remaining sections of this paper is as follows:

- The following two sections review the most appropriate literature for classifying megascience projects and personified concepts of leadership in science and technology.
- The methodology section will address the research methods used for conducting this research.
- The two sections following this will identify and discuss the findings. One particular point will be to address the reasonable comment that if the heterogeneous engineer concept is not representative in megascience projects, what are the characteristics of such leaders.
- The final section will summarise the conclusions of this paper and proposes what research opportunities exist for further development of this work.

Megascience Projects

This section addresses the novelty of megascience projects as a subcategory of the broader megaproject literature with an additional dimension of at least a high level of technological uncertainty, making them a worthy topic of investigation. This paper also considers the primary personified concepts of leadership in high technology projects and justify my focus on the heterogeneous engineer.

Although the concept of 'Big Science' is well-documented in the literature (De Solla Price, 1963), it refers to the industrial scale of production of scientific papers and knowledge. Although Big Science projects are identified in the literature (Hughes, 2002; Liyanage and Boisot, 2011), this term is used primarily to appeal to wider elements of society as the term is broadly appreciated. The term megascience project has only recently come into use, but appears to be of greater academic utility. The Organisation for Economic Cooperation and Development (OECD) created a megascience forum in the early 1990s (Redfearn, 1996); the term was later adapted by Hoddeson *et al*. (2008), who characterised megascience as a trend emerging from the 1970s Oil Crises as a means to unlock new experimental fields and also as a way to guarantee long term government funding. This term acted as a useful link into the broader megaproject literature and Eggleton (2017) identified megascience projects as a distinct subcategory of the broader megaproject literature that incorporates the additional dimension of a high or 'super high' level of technological uncertainty.

Megaprojects

Megaprojects are a relatively broad category of project with the primary inclusion criterion being that it must have a budget of at least one billion US dollars in 2012 prices (Flyvbjerg, 2014). This results in projects as diverse as airports, bridges, rail systems, and tunnels coming under the broad category of megaprojects (Davies, Gann, & Douglas, 2009; Flyvbjerg, Bruzelius, & Rothengatter, 2003). These megaprojects are traditionally constructed for infrastructure to enable to economic growth rather than as revenue drivers in themselves and therefore their value cannot be adequately captured with traditional methods (Flyvbjerg, 2014). The financial and industrial scale of megaprojects often make it nearly impossible for any single organisation to have the ability to manufacture all components (Mersino, 2007; Flyvbjerg, 2014). This often necessitates subcontracting component manufacture to third party vendors (Mersino, 2007; Flyvbjerg, 2014). Such subcontracting may consume a significant proportion of global supply, as evidenced during the construction of the LHC, which caused a global shortage of some materials (Evans, 2009), as well as raising challenges of coordination and of manufacture within tight component tolerances. Issues of scale, coupled with associations with economic growth, give megaprojects an association with national prestige which makes governments a substantial stakeholder and funder of these projects (Flyvbjerg *et al.*, 2003). The success or failure of a megaproject can even precipitate the rise or fall of an entire economic sector, as with the Superconducting Supercollider project, the collapse of which led to the decisive relocation of much of the high energy physics field to Europe (Fraser, 1997).

A second issue with megaprojects is the issue of complexity. Most projects are scoped as systems which often have a single geographic focus and relatively few points of failure (Shenhar and Dvir, 1996). However, megaprojects tend to be constructed as complex arrays comprised of several dispersed systems working towards a common goal (Shenhar and Dvir, 1996). Any failure in any single component within any system can propagate and cause the entire array to perform sub-optimally or fail. This additional layer of complexity is one of the hallmarks of a megaproject and is a frequent cause of major cost overruns. Table 1 illustrates the Shenhar and Dvir (1996) scope classification system:

Project scope category	**Description**	**Example**
Assembly	Collection of components into a single unit capable of performing limited functions	Household appliance
System	Complex collection of many assemblies capable of large scale independent functions	Personal computer
Array	A collection of systems working in conjunction towards a common goal	Public transport network

Table 1: The classification system for project scope proposed by Shenhar and Dvir (1996)

These cost overruns and even substantial schedule delays are considered a normal part of megaproject management with the primary criterion of success becoming so diluted that project success can be defined simply by project completion (Flyvbjerg *et al.*, 2003). Cost and schedules are often viewed by scholars and practitioners as very optimistic even at early stages (Flyvbjerg *et al.*, 2003). These megaprojects are also traditionally organised according to a client and delivery partner model, whereby the organisation broadly defines the goals and specifications of the systems and invited bids for the contract to build and realise the details as the organisation rarely has the technical expertise available internally (Davies and Mackenzie, 2014; Davies, 2017). However, in megascience projects this technical competence is present (Evans, 2014). This can even result in the laboratory taking a direct role in component manufacturing and making changes to prevent the issue of faulty components damaging the machine (CERN, 2008).

Technologically uncertain projects

As noted above, megascience projects are an unusual subcategory of megaprojects in that they also incorporate a high or ‘super high’ level of technological uncertainty. Most projects are organised using relatively standardized tools that assume budgets and timetables will remain fixed (Shenhar and Dvir, 1996; Pinto, 2012). This is often because the technologies used in the project are well-understood and there is a low risk that fundamental issues will need to be re-examined from first principles (Shenhar and Dvir, 1996). However, when a project reaches a certain level of technological uncertainty, these managerial assumptions may be inappropriate. One alternative approach amounts to a shift to a more flexible style as fundamental technologies may need to be re-developed, even at a late project stage, and managers will need to accept or even embrace this uncertainty (Shenhar and Dvir, 1996). Shenhar and Dvir (1996) classified projects into four discrete categories from class 'A' , which incorporate standard technologies in traditional ways, to class 'D' where technology must be developed in the context of application. A full description of the categories is contained in Table 2:

Classification of Project	Level of Technological Uncertainty	Description	Example
A	Low	Familiar technology used in familiar ways	Bridge[3]
B	Medium	Adaptation of familiar technology possibly incorporating new features	Mobile phone
C	High	First use of new technologies that already exist	Space Shuttle
D	Super High	Development of new technology in the context of application	Apollo Program

Table 2: The project technological uncertainty classification system proposed by Shenhar and Dvir (1996)

As can be observed from Table 2, most megaprojects and infrastructures tend to incorporate well-understood technologies with the primary issues being the application of the technology at a much larger scale. This would make them class 'A' or class 'B' projects based on this classification system. However, megascience projects often incorporate brand new technologies or even technologies specifically developed

[3] This is a generalisation, as some bridges historically have had a certain degree of technological uncertainty eg. the first steel bridge and the first major suspension bridge. However, bridges built today generally possess a low degree of technological uncertainty, as noted by Shenhar and Dvir (1996).

for the project. This puts megascience projects in the class ‘C’ or even class ‘D’ categories, which necessitates very different managerial attitudes to design changes even at late stages of the project.

Although there is relatively little work investigating leadership in the context of megascience projects such as the LHC, there is some work examining leadership in the context of one of the LHC experimental collaborations: ATLAS (Liyanage and Boisot, 2011). Liyanage and Boisot (2011) identified three streams of leadership: institutional, intellectual, and project. CERN provides the institutional leadership for ATLAS by providing a framework for the collaborations to organise themselves within. Intellectual leadership is a temporary status granted by the community based on an individual’s superior skills and knowledge. According to Liyanage and Boisot (2011), there are no ‘heroes’ in ATLAS which is slightly at odds with the concept of the heterogeneous engineer which is a clearly heroic concept (Krige, 2001). The final stream of project leadership within ATLAS describes the degree to which a leader can improve team capabilities.

Conducting this research involved stratifying the organisation into three strata (Mumford *et al.*, 2007). This followed the principles of Mumford *et al.* (2007) who divided organisations into junior, mid, and senior levels as there are differing skills requirements depending on the strata (Katz, 1974). Figure 1 and Figure 2 illustrate the divisions used for this research and the institutional leadership that CERN provides.

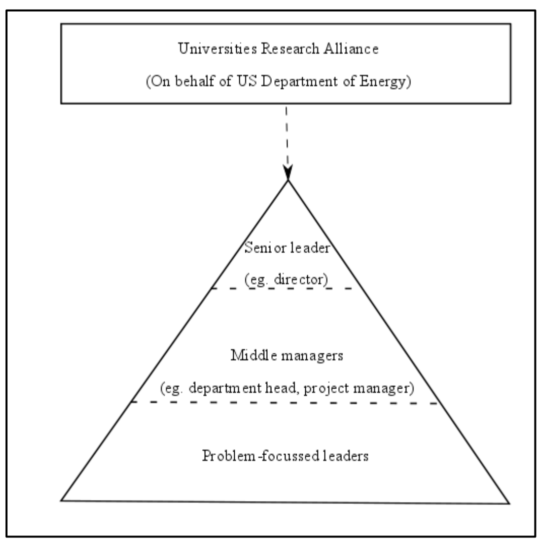

Figure 1: Diagram showing the organisational structure of Fermilab in the context of the three-level model for analysing leadership

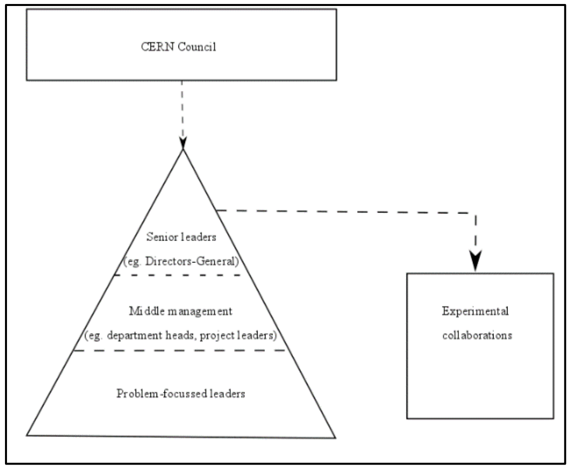

Figure 2: Diagram showing organisational structure of CERN in the context of the model for analysing leadership. Also illustrated is the indirect link between CERN and the experimental collaborations, described as institutional leadership

Personified concepts of leadership for large scale projects

There are two particularly relevant conceptual frameworks for personified leadership in scientific and high technology projects. These are the heterogeneous engineer developed by Krige (2001), which is the primary focus of this paper, and the systems builder, which is particularly associated with Hughes (1998).

The systems builder

Although this paper focusses primary on the concept of the heterogeneous engineer, it is not the only personified concept of forces shaping systems (Hughes, 1987; Elkins and Keller, 2003). The concept of the systems builder is particularly prominent within the large technical systems literature (Hughes, 1987). A single large technical system is composed of components which may be physical artefacts or non-physical in nature (Geyer and Davies, 2000). These components interact with one another in a particular configuration, meaning that a single change in any one sub-system may cascade consequences across the entire system (Hughes, 1987; Geyer and Davies, 2000). These systems are limited by controls either from physical artefacts or human operators (Hughes, 1987): they are composed of both technological and social components. There is some literature discussion concerning the identification of the technical-social boundary and the interface between the two facets (Joerges, 1996). Such large technical systems include the USS Nautilus (the first nuclear powered submarine), the ARPANET (an early version of the internet), and the Boston Central Artery/Tunnel project (Hughes, 1987, 2004).[4]

[4] Often referred to colloquially as the ‘Big Dig’.

Hughes (1998) characterises a systems builder as an individual or organisation in charge of a technological project from beginning to the end, crossing disciplinary and boundaries as necessary. However rather than seeing a systems builder making detailed technical choices, Hughes (1998) suggests a focus on the interfaces between components to ensure that the final product will run smoothly. It is also noted that he characterised 'system builders' as "…like 'heterogeneous engineers'" (Law, 1987b,) thus establishing a degree of overlap between these two concepts. However, the heterogeneous engineer concept was considered most relevant for this research and the justifications for its selection is in the heterogeneous engineer section of this paper. Two of the large technical systems identified above are valuable for discussing the concept of the systems builder - the Atlas[5] intercontinental ballistic missile project and the SAGE (Semi-Automatic Ground Environment) air defence project.

The Atlas project was the effort to build the first American Intercontinental Ballistic Missile (ICBM), a significant development in the field of systems engineering (Morris, 2013). Although withdrawn from military service after a relatively short period, the leftover units proved adaptable for civilian rocket launches as the Americans scrambled to develop their space programme after the Soviet launch of Sputnik (Morris, 2013). Therefore, one might argue that its real value was as a learning exercise for project managers in the management of a large technical system. The organisation of such an effort proved a challenge equal to the technical issues (Hughes, 1998). One prominent committee recommended the creation of a new independent management organisation, staffed by the most technically competent scientists. This is highly significant, as scientists lead megascience projects whereas other megaprojects generally turn to professional project managers to organise the effort. Hughes (1998) identified two individuals as systems builders during the Atlas project – Bernard Schriever and Simon Ramo. While neither are characterised as 'heroic systems builders' who made all of the technical decisions, they both maintained a focus on the project and their teams while refusing to give into political pressure when it would have impeded their teams (Hughes, 1998). This demonstrates the system builder ideal as an individual who maintains a focus on realising the system without giving into external pressure. However, one must also observe the identification of the sub-category of 'heroic systems builder' who involves themselves in detailed technical minutiae. As shall be identified below, the heterogeneous engineer also involves themselves in detailed technical minutiae and political issues (Krige, 2001).

[5] Note that there is a difference in this paper between ATLAS and Atlas. ATLAS is the acronym given to an LHC experimental collaboration and detector that stands for A Toroidal LHC ApparatuS with the collaboration first forming in the 1980s and is still active. Atlas refers to an American missile developed in the 1950s that was re-purposed as a rocket during the early stages of the US space programme before its retirement in the mid-1960s (Hughes, 1998).

Both the SAGE project and the Atlas project occurred during the first phase of the Cold War, before détente (Hughes, 1998). However, while the SAGE project began at a very early stage in the Cold War when many traditional project management methodologies were in infancy, the Atlas project occurred during a particularly tense period of the Cold War, by which time these methodologies had become more developed (Morris, 2013). The SAGE project was an air defence system that used a combination of computers and radar to plot the course of an incoming plane or missile. Previous air defence systems that used radar and physical plots of planes sufficed for propeller planes, but their inefficiencies would have led to unacceptable delays when plotting jet-powered planes. SAGE automatically plotted these coordinates and updated them in real-time. Although computer prototypes existed which worked on a small scale, the challenge was to expand this system to provide coverage of an entire continent. The Massachusetts Institute of Technology (MIT), which had extensive expertise in electronic research and radar as separate disciplines, was characterised by Hughes (1998) as the systems builder for creating a laboratory dedicated to air defence work. This demonstrates that it is possible for an organisation to be a systems builder and that it is not purely a personified concept.

The heterogeneous engineer

The concept of the heterogeneous engineer is a personified form of heterogeneous engineering as developed by Law (1987b). A heterogeneous engineer is a single individual who is capable of mobilizing the necessary technical, human, and political resources to secure objectives (Krige, 2001). Rubbia played a leading role in convincing CERN management that his proposed experiment was feasible and in organizing the endeavour. This caused a substantial change in the laboratory culture, from one that practiced a risk-averse 'gold plated' style of science (Irvine and Martin, 1984; Martin and Irvine, 1984b, 1984a), to one that more readily embraced risk at Fermilab, which had a history of rivalry (Lederman and Laboratory, 1983; Krige, 2001; Evans, 2009).

Law (1987a) illustrated the concept using the shift in Portuguese naval focus from the relatively sheltered waters of the Mediterranean to the far rougher seas of the Atlantic ocean due to the traditional overland trade routes to the east becoming non-viable during the 15th and 16th Centuries. The Portuguese ships were described as systems, composed of material and human experiences. The changing focus in the Portuguese navy resulted in the discovery that its ships were inadequate for the West African coast as both the human and material experiences developed in Europe and the Mediterranean were unsuitable for new actors off the west African coast (Law, 1987a). The first deficiency was the oar-powered propulsion, which sufficed for the Mediterranean but was very inefficient for traversing expanses of ocean. Secondly, their present navigational tools and methods were unsuitable for the Atlantic and Indian oceans. These two challenges were resolved through ship redesigns, the development of new navigational technologies, and the incorporation of safer routes into maps (Law, 1987a). These new ships even proved adaptable to unexpected actors (Law, 1987a). This was illustrated when, having already constructed a system sufficiently robust to round the Cape of Good Hope, Portuguese ships encountered hostile forces in the Arabian Peninsula (Law, 1987a). At that time the Portuguese fleet had not previously encountered serious opposition but could retro-fit cannons to existing systems to counter this new threat (Law, 1987a).

A heterogeneous engineer likewise brings together the necessary technological, human, material, and financial resources to achieve scientific discoveries (Krige, 2001). The novelty of Krige (2001) was to expand on these brief statements by Law (1987b, 1987a) that individuals could embody heterogeneous engineering and introduce a personified conceptual framework.

Krige (2001) considered this in the case of Carlo Rubbia's award of the 1984 Nobel Prize for physics for his role in the discovery of the W and Z bosons, which mediate the weak nuclear force (Arnison *et al.*, 1983; Banner *et al.*, 1983; Krige, 2001).[6] The awarding committee noted that the marriage of his knowledge and enthusiasm was what convinced the CERN management that such a project could be accomplished (Krige, 2001). The committee also noted he was responsible for building a team of scientists to implement the project. Five primary criteria defined the importance of Rubbia's project (Krige, 2001). These were a clearly defined physics objective, technological innovation, the acquisition and management of human and material resources, unwavering buy-in from laboratory management, and that success could strike a new balance in scientific power between the United States and Europe (Krige, 2001).

During the 1970s, a new innovation in magnet technology allowed physicists to achieve higher energy collisions by designing accelerators that could sustain the orbit of two hadron beams in opposite directions before colliding these beams (Hoddeson *et al.*, 2008).[7] Several laboratories that had an interest in these colliding beams devised experiments to test their technical feasibility (Krige, 2001; Hoddeson *et al.*, 2008). The first hadron collider constructed at CERN, the Intersecting Storage Rings (ISR), collided two beams of protons at approximately 62GeV (Krige *et al.*, 1997). ISR had the potential to make many new discoveries, but design limitations effectively forced physicists to use it as a proving ground for technologies and methods intended to improve the beam quality in future colliders (Krige *et al.*, 1997). Two possible methods existed to improve the luminosity or particle density of a hadron beam, electron cooling and stochastic[8]

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[6] Krige (2001) also briefly mentions Charles Draper of the MIT Instrumentation Laboratory as a heterogeneous engineer, but the topic of the paper is clearly Carlo Rubbia.

[7] Previously physicists made use of fixed-target hadron colliders, where a single beam collides with a static target. It should be noted that lepton colliders had been operating ten years before ISR.

[8] Stochastic cooling is a means of preventing beam spread by using a small electric kicker to reduce the transverse momentum of a beam over the course of multiple beam orbits in a synchrotron (Van der Meer, 1995).

cooling, with experiments conducted in the Soviet Union and at CERN respectively (Krige, 2001). Carlo Rubbia was part of a collaboration that proposed to Fermilab the idea of incorporating these cooling methods to collide particles and antiparticles, a proposal was rejected as “premature” (Rubbia *et al.*, 1977; Rubbia, 1985; Krige, 2001). This collaboration was later invited by CERN to conduct their work using the Super Proton Synchrotron (SPS) (Krige, 2001). CERN wished to reverse a trend whereby their lack of audacity had resulted in CERN making few discoveries, while Fermilab’s comfort with audacious statements had paid off with several discoveries and awards (Irvine and Martin, 1984; Martin and Irvine, 1984a, 1984b; Krige *et al.*, 1997; Krige, 2001). These two laboratories developed at a similar time and this fostered a sense of rivalry (Lederman and Laboratory, 1983; Krige, 2001; Hoddeson *et al.*, 2008).

Rubbia took a significant role in the effort at CERN and began to display the behaviours Krige (2001) associated with the heterogeneous engineer. Firstly, Rubbia secured buy-in from senior figures by arguing that success would bring acclaim to CERN (Krige, 2001). Secondly, he was able to create a more risk-favourable environment at CERN and rapidly mobilised the necessary human resources to ensure a unified endeavour (Krige, 2001). Thirdly, rapid approval of finance was secured by exploiting a loophole within the CERN framework – new accelerators require consultation and special funding from member states while experiments do not (Krige, 2001). Rubbia successfully argued that the proposed accelerator infrastructure changes were part of an experiment which allowed the funding to come from the annual operating budget without consulting the member states (Krige, 2001). In this way, Rubbia, as a heterogeneous engineer, was able to bring together the structural, human and financial factors necessary to ensure a successful project outcome.

This conceptual framework of the heterogeneous engineer obviously has a significant overlap with the ‘heroic systems builder’ (Hughes, 1987; Joerges, 1996). However, while the literature tends to describe the heroic systems builder as deeply involved in just detailed technical matters (Hughes, 1998), the heterogeneous engineer mobilises *all* the necessary resources to achieve their goals (Krige, 2001). This includes human, financial, and political factors which seems to fit the documented behaviours of leaders within particle physics (Heilbron *et al.*, 1981; Krige, 2001; Hoddeson *et al.*, 2008). Therefore for this particular research, the heterogeneous engineer is the most appropriate conceptual framework for three additional reasons. Firstly, this research proposed to investigate leadership in megascience projects. Therefore, it was sensible to select the conceptual framework that was in the most similar domain. Secondly, Carlo Rubbia played an important role in the early life of the LHC so the heterogeneous engineer concept offered a valuable opportunity to provoke discussion during the fieldwork. Thirdly, the heterogeneous engineer offered significant links to the broader field of heterogeneous engineering. These three primary reasons justified the selection of the heterogeneous engineer as the conceptual framework.

Methods

Data collection

This study developed two case studies by employing two different research methods using two megascience projects at laboratories that Rubbia had extensive experience in – the Tevatron at Fermi National Accelerator Laboratory in Batavia, IL, USA and the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. The justification for the selection of case studies lies in the inherent value in a single unusual case (Stake, 2005). Both Fermilab and CERN have individually been the subject of significant research from the history of science and science policy communities (Irvine and Martin, 1984; Martin and Irvine, 1984a, 1984b, Hermann *et al.*, 1987a, 1987b; Hoddeson *et al.*, 2008). The development of two case studies allowed the determination of what is unique to a single context and what may be considered a reliable foundation for broader theory development (Yin, 1994; Stake, 2005). However, there is relatively little work examining two or more laboratories which allows cross case comparisons (Traweek, 2009). Such a strategy for this research provided a wider basis for this work.

The two research methods employed were archival research followed by a programme of semi-structured interviews. The first research phase involved examining the relevant archival information contained in the archives of each of the laboratories. In the case of CERN, this required the successful negotiation of exceptional access to restricted areas within the CERN archives. The intent of this archive research was to gain an understanding of the internal atmosphere of each laboratory and identify key disputes or decisions to bring into the interview phase of the research as discussion prompts.

The second phase of the research, the semi-structured interviews, involved interviewing key individuals about leadership topics, their experiences, and their reactions to key decision-making points that arose during the archival research phase. Fifteen interviews were conducted at each of Fermilab and CERN, representing a broad cross section of the laboratory including senior leaders (such as the Fermilab directors and CERN Directors-General), project and departmental heads, and those who worked as section or group leaders at the laboratory. Many of the interviewees had spent time at both laboratories and so offered comparative comments. The pool of interviewees was developed using a snowball sample (Atkinson and Flint, 2001). Such a process involved the researcher asking an interviewee whether there was anyone else would might also be in a position to contribute. This enabled the rapid accumulation of a suitable pool of interviewees as one could easily tap into social networks within the laboratories (Thompson, 1997; Atkinson and Flint, 2001). The duration of these interviews varied from one to three hours. During the discussions it was natural that many individuals would discuss the senior laboratory management and offer their own opinions – Carlo Rubbia was a frequent subject of those discussions.

Data analysis

Analysis of the interview data was conducted on a thematic basis. There were concerns that using a textual or discourse analytical approach would lead to 'off the cuff' remarks from interviewees having un-due influence over findings. This ultimately reflected challenges relating to precision and accuracy. Textual or discourse analysis offers an analytical tool with a high level of precision (McKee, 2003). However, applying such tools with a fine resolution would have likely led to inaccurate conclusions when used to analyse interview data, which has issues with selective memory, justifications of decisions using *post-hoc* information, and loss of opinion caused by deaths (Valenzuela and Shrivastava, 2002). Therefore, examining the broad themes of the interview data is more appropriate in this case. Figure 3 illustrates the process of the study.

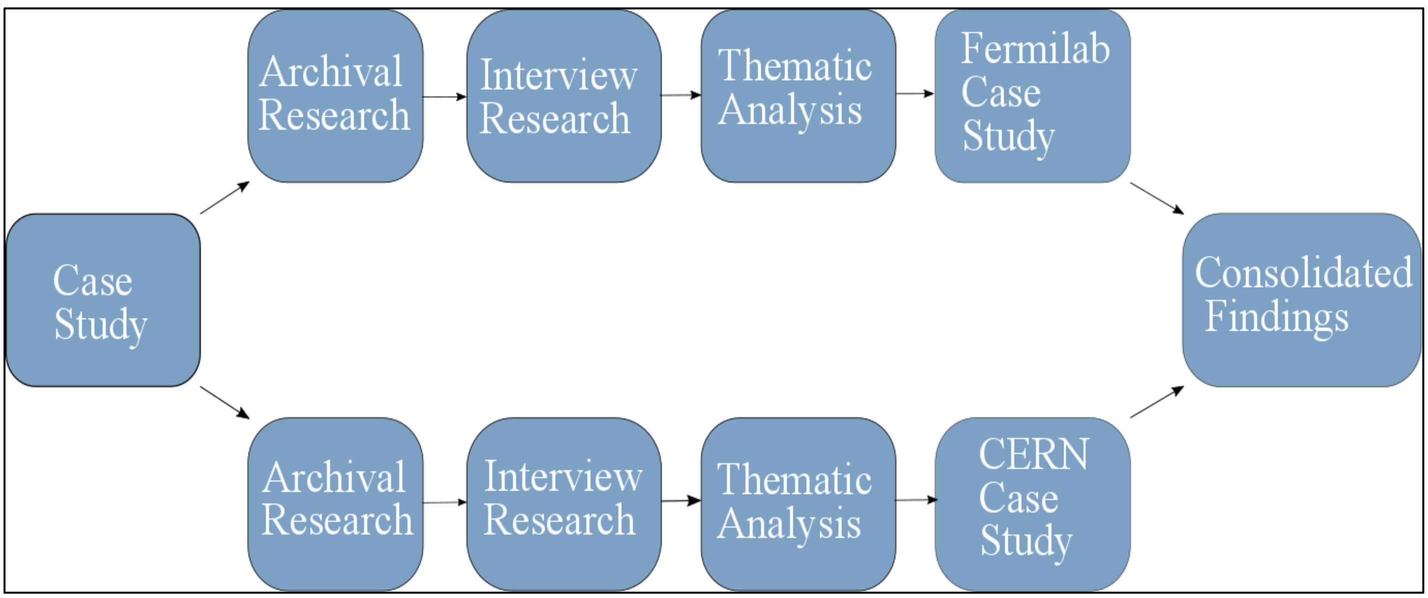

Figure 3: A diagram illustrating the study protocol

Findings

Although this study examined leadership in megascience projects more broadly, interviewees frequently discussed Carlo Rubbia, both for his central role in the discovery of the W and Z bosons and for the actions as CERN Director-General in relation to the LHC. It rapidly became obvious that Carlo Rubbia was a relative anomaly both amongst experimental collaborations and amongst accelerator constructors. All CERN interviewees working with him as challenging as this quote from C1 demonstrates:

> *"As far from real management as you could possibly get. Everyone loved him, but he was hell to work with. Charismatic. Unpredictable. Carlo Rubbia could*

destroy you if you weren't of strong character. He almost alienated people but still putting out wacky ideas even now!" (Source: C1)

What is clearly apparent from the quote above is that in spite of the challenges involved with working with Rubbia, he clearly inspired devotion amongst his colleagues. While all interviewees at CERN characterized Rubbia as a challenge to work with, twelve of them volunteered that it was difficult to see any other individual securing such an ambitious machine's place in the laboratory's strategy as these quotes from Interviewees C11, C16, and C6 illustrate:

"Carlo Rubbia had the vision back then" (Source: C11)

And:

"Carlo Rubbia had to launch and defend LHC. But he was credible and people just followed him" (Source: C16)

And:

"Carlo Rubbia… really developed CERN, kept the LHC dream alive" (Source: C6)

The interviewees felt that Carlo Rubbia might have been difficult to work with; but because of these attributes, he was able to bring together the appropriate resources to secure the LHC's place in laboratory strategy. However, it did come with the risk that laboratory stakeholders became overly dependent on him, this prevented full debates over laboratory strategy as these quotes from Interviewees C4, and C2 described:

"I knew his reputation but the meeting of the directorate was incredible as they were like mice around him." (Source: C4)

And:

"You could never grow a leader like him using a textbook… [but] I could see the culture of fear he left" (Source: C2)

This demonstrates how a heterogeneous engineer can potentially damage an organisation. The tendency of a heterogeneous engineer to centralize resources and decision-making within themselves can lead to a power vacuum upon their departure. However, the study originally sought to use this heterogeneous engineer concept as a basis for developing broader theory, so the interviewer was expecting to identify several heterogeneous engineers who centralized decision making within themselves. However, what actually emerged were statements that Carlo Rubbia was a unique individual. Rubbia was so unique in fact, that one could not train his characteristics, but he had a tendency to begin projects but tended to have challenges in completing them according to Interviewees C6 and C5:

> *"[Rubbia]… could have achieved more if he mastered himself. He had this tendency to flit between projects. I thought it was his way, seeking leadership to escape his present" (Source: C6)*

And:

> *"One Christmas Eve I was about to leave at 7PM, when I suddenly get this four-page proposal for another experiment [From Rubbia]. A brilliant mind, got results but not able to produce a community or the next generation" (Source: C5)*

One might reasonably ask why the scientific community was so willing to accept Carlo Rubbia when he was such a challenge to work with. Interviewee C15 had a very interesting observation that captured the attitudes of the four interviewees who commented:

> *"…they looked past it because he was the guy who could reach the goal. They knew he would deliver" (Source: C15)*

At Fermilab, most of the comments concerning Rubbia also related to his time at CERN rather than while he worked in the United States. However, six of the Fermilab interviewees identified another individual as having characteristics that were rather to Rubbia – namely Fermilab's founder Robert Wilson. This quote from Interviewee F1 first showed the attitude that although Wilson was beloved by the laboratory; there were some indications that, like Rubbia, he could be divisive:

> *"I've spent 20 years working with Bob [Wilson] even before FNAL [Fermi National Accelerator Laboratory, the formal name for Fermilab]. Bob [Wilson] was driven, forceful – build it quick and cheap, then fix it." (Source: F6)*

Interviewee F1 further underlined this issue by describing his forceful nature in a specific circumstance:

> *"Wilson was a transformational leader with authoritarian characteristics. He had vision and charisma and was definitely highly motivated but drove people out… There was once a plan to expand a building, the plan made it bigger than*

strictly necessary, Bob wasn't happy and screamed at the architect at the practice presentation, but when presented it was accepted as is" (Source: F1)

Wilson took personal control of key decisions both during the foundation of Fermilab and during the early stages of the Tevatron. These included very unusual issues such as the design and layout of the main administrative building (Hoddeson *et al.*, 2008), and very detailed technical decisions in relation to the Tevatron. As Interviewee F7 notes, these technical decisions sometimes needed alteration by others but Wilson appeared to regard such alterations as unimportant compared to achieving the final goals:

"… Bob [Wilson] would need people to clean up his ideas to make them work. He cut the budget for magnets and almost got into trouble for it… Cornell had to step in to fix his designs on more than one occasion. Luckily, with the Tevatron, Helen Edwards [the project leader for the Energy Doubler/Saver] insisted that the machine would need correction coils… Bob [Wilson] just wanted his 1TeV." (Source: F7)

The description of Wilson as exhibiting a desire to become involved in detailed technical aspects of the machine design but being open to being overruled by colleagues is slightly at odds with the traditional image of a heterogeneous engineer (Krige, 2001). The interviewees described this as being very forceful, yet surprisingly relaxed about other aspects of the project, as this quote from Interviewee F11 illustrates:

"Now Bob [Wilson] was forceful, always pushing people to do more. He was the best project initiator but not the best listener… Despite his forceful nature, he was very laissez-faire when it came to other things." (Source: F11)

This quote demonstrates a certain difference between Rubbia and Wilson. While Rubbia is characterized in the literature as taking control over every resource during the process of discovering the W and Z bosons (Krige, 2001), Wilson seemed to be somewhat more selective about which details to be directly involved in. Trying to understand Wilson's priorities was therefore key. What emerged from the interviews was that Wilson's ultimate aim was to achieve 'headline' beam energies that would draw in researchers to conduct their experiments at what has been referred to by Hoddeson *et al*. (2008) as the 'energy frontier'. The quote from Interviewee F4 illustrates this attitude in contrast to the second Fermilab director Leon Lederman:

"Bob [Wilson] would build with the assumption that if you build it, then the experimental ideas will come. His [Wilson's] main metric for measuring success

was machine performance… Leon [Lederman] had ideas about how to experiment on it while building." (Source: F4)

What emerges from this study is that individuals such as Carlo Rubbia and Bob Wilson, who tend to centralize decision making within themselves and seek obedience from their peers, are relatively rare amongst scientists as opposed to other high technology sectors where they appear to be more common (Kidder, 1981; Isaacson, 2011). Many of their colleagues may even find such individuals challenging to work with, but they have a utility concerning the initiation of significant endeavours such as the conception of a new laboratory or new apparatus. During such a period, a heterogeneous engineer is able to bring together all the necessary resources to secure good outcomes. However, the challenging nature of working with a heterogeneous engineer means that, upon securing the project's place in laboratory strategy, the heterogeneous engineer should strongly consider handing over project control to a new leader who can build alliances amongst stakeholders to secure the changing needs of the project. Furthermore, there is evidence to support a conclusion that the heterogeneous engineer concept proved to be a poor foundation for developing wider leadership theory, which is below in the discussion section.

If the heterogeneous engineer is not broadly representative of leaders in megascience projects, then one might reasonably ask: what are the characteristics of these leaders? This proved to be the key topic during the interview research, with the interviewees dividing leadership according to two broad communities: the first was accelerator constructors and the second was the experimentalist community. According to all of the CERN interviewees, experimental collaborations were far more democratic compared to the conclusions reached by the accelerator constructors, with decisions made based on consensus as this quote from Interviewee C12 demonstrates:

"It's much harder to be a spokesperson as everything has to be by consensus. It's less efficient but you can't do it any other way. It can be very hard to align all vectors rather than have scalar effort." (Source: C12)

This division was allegedly a product of both funding arrangements and the technologies used as illustrated by these quotes from C13, C14 and C15

"LHC is run by CERN with a normal hierarchy; CERN controls the resources in an 80:20 split with 20% held externally. CMS [One of the experiments] is principally externally funded with 20% CERN resources and 80% held externally. It leads to an experimental spokesperson who's the boss but not

> *really. It leads to a very different style, a much more convincing style trying to always reach a democratic consensus." (Source: C13)*

And:

> *"Most money is central with LHC. All of the parts must work otherwise LHC won't work; if it works without that part then why is it there? With ATLAS [one of the experiments] no money is held centrally and bits can work not quite up to scratch and the machine will still work" (Source: C14)*

And:

> *"ATLAS knows the minimum [technical] requirements but will innovate until the last minute. LHC is similar to space science – lots of effort goes into the design, then it's handed over to industry to fabricate" (Source: C15)*

There were even differences in leadership characteristics between the two experimental collaborations investigated for this research: ATLAS and CMS. Interviewee C15 in particular described his own position at ATLAS:

> *"…it's an elected position although there's a selection committee for two years and a higher majority is required for subsequent terms." (Source: C15)*

This principal difference is because of the very different pathway taken by ATLAS compared to CMS. While CMS emerged from a small group of researchers working on the LEP UA2 experiment in the 1980s, ATLAS was the result of two experimental collaborations merging to improve their chances of being selected to occupy one of the six LHC experimental caverns (Tuertscher *et al.*, 2011). Nonetheless, the interviewees considered it acceptable for experimental leaders to exploit the style and rhetoric of democracy while secretly securing their preferred pathway – referred to as '*guided democracy*'. This even occurred at Fermilab as the quotes below illustrate:

> *"Leon [Lederman] kept his own counsel and decided for himself, possibly even before the presentations had started but he needed to give the impression of democracy." (Source: F2)*

And:

> *"Transformational with democratic leadership works but it needs a guided democracy. Technical decisions can't be a vote – it either works or it doesn't. But if one can get a consensus, then a vote isn't needed." (Source: C8)*

And:

> *"Sometimes it's useful to give the impression of democracy, but a guided democracy like Singapore." (Source: C4)*

This seems to be a relatively underreported phenomenon, as the literature review identified only a single observation of a guided democracy in the 1950s and no description of what it meant in a science project context (Krige *et al.*, 1997).

Although the differing financial and technological arrangements result in differences between accelerator and experimental projects, there were still many common characteristics between the two communities. The most foundational of these characteristics was *technical competence*. A leader without technical competence would struggle to gain the respect of his or her team. The quotes below illustrate the attitudes held by all the interviewees:

> *"… most important to gain the respect of people with your technical ability. Authority needs ability." (Source: F2)*

And:

> *"Leaders need vision, intuition in the absence of quantification, and technical skills." (Source: F7)*

And:

> *"The most important component [of leadership] is technical competency, from which comes respect." (Source: C6)*

And:

> *"A leader has to know more or less the intended direction, choose the right people to be complementary but above all else they must be technically competent." (Source: Interviewee C4)*

The second and third principle characteristics of leaders in megascience projects have strong links to one another. These relate to *team empowerment* and *trustworthiness*.

> *"Optimism and assurance are needed quite frequently though. Like conducting an orchestra... Everyone has to focus on their part and keep faith with the rest; otherwise they can't do their own role well." (Source: C7)*

And:

> *"If you have a good stallion, then you let him take the reins sometimes." (Source: F3)*

And:

> *"…show your confidence in the people but don't just turn them loose. Push them but not beyond reason." (Source: F6)*

And:

> *"Being a leader depends on the department and role. But ultimately it's about empowering people and show[ing] off the talents of the team." (Source: C12)*

The fourth characteristic of leaders in megascience projects was universal according to all of the interviewees – *charisma*. However, there was some debate amongst the interviewees as to the definition of charisma. The Fermilab interviewees seemed to define charisma in terms of memorable statements or acts, whereas CERN interviewees viewed charisma as an enthusiastic attitude towards problem solving. The following quotes from Interviewees F5, F8, C9, and C5 demonstrate both the Fermilab and CERN definitions of charisma:

> *"I threw my hat in the ring when NAL [National Accelerator Laboratory – the original name for Fermilab] first came up. Bob [Wilson] interviewed me with the statement 'What can you do for me?'" (Source: F5)*

And:

> *"We first met on my birthday, Leon [Lederman] was being given this tour by some guys from URA [Universities Research Association – the consortium that runs Fermilab] – and we were celebrating my birthday with some champagne.*

Leon [Lederman] came over looking slightly stern and asked 'Why are we celebrating your birthday?' to which I said 'Well, I'm not dead yet'. Well Leon [Lederman] just beamed and said 'That's a great response, have another glass of champagne'." (Source: F8)

And:

"Be charismatic and friendly so people will approach you with their opinions." (Source: C9)

And:

"When people have a problem and it's difficult, the future leaders accept and enjoy the challenge. That charisma is easy to see. The challenge excites them" (Source: C5)

These quotes demonstrate is that while the interviewees identified charisma as an important characteristic of leaders, there was no uniform definition of the term. The general thrust of the comments indicated that their definition included an enthusiastic attitude towards problem-solving and inspiring teams towards devising solutions.

The fifth characteristic was particularly prominent amongst those leaders serving in 'middle management' roles such as project leaders or departmental heads: *management ability*. At lower levels of the organisation, leaders did not require such skills as their task was to focus on the technology and problem solve. The middle managers role is to represent such teams and acquire resources for these problem-focussed teams. Towards the end-stages of a project, these management abilities shifted to become rather more transactional. By this time, there should be solutions to the major technical challenges, so the middle manager can focus on more traditional project issues such as staying on schedule and budget as these quotes from Interviewees C6, F5, and F2 show:

"Some roles need managerial skills but not leadership. The Physics Department runs a smooth operation but it doesn't lead. That's the job of research. Management keeps the trains running on time but leadership builds the train line" (Source: C6)

And:

"Leaders use much broader statements and allow the deputies to do the dirty work." (Source: F5)

And:

"Scientists are not drones, they're intelligent people. Having said that, you can definitely be transactional at the end stages when things are more certain." (Source: F2)

The final principal characteristic of leaders in megascience projects was generally restricted only to senior leaders (ie. Directors-General and directors). The concept of a *vision* is common within the leadership literature and is often associated with transformational leadership (Bass, 1990). Likewise, senior leaders require a vision as a tool to unite the laboratory towards a single goal as these quotes from Interviewees F6, F7, and C16 demonstrate:

"When Bob [Wilson] arrived, very soon he wanted to build a superconducting ring accelerator. Focussed on building it and the lab." (Source: F6)

And:

"Bob [Wilson] always had a plan for a bigger machine than the Main Ring… when superconductivity appeared on the horizon; Bob [Wilson] noticed its potential and started quietly moving things." (Source: F7)

And:

"Carlo Rubbia was doing LEP but left room for the hadron collider. The DG can't be a manager but has to follow science, the scientists wanted a neutrino beam, but Carlo knew that a large hadron collider had the science… [you] can't be revolutionary with an institution - you have to be more cautious but you can't just follow public opinion." (Source: C16)

However, once a vision exists, it is not necessary for other senior leaders to develop their own vision. These subsequent senior leaders can instead refine the original vision to make it achievable as the quote below illustrates:

> *"Being a leader is about having a vision which wasn't needed in my case but I could articulate it… Sell the vision to get funding while finishing what came before." (Source: C14)*

These quotes show a direct link from the original visions for the LHC and the Tevatron to Carlo Rubbia and Robert Wilson respectively, identified above as heterogeneous engineers. This demonstrates that while the heterogeneous engineer concept is not a good foundation for the development of broader leadership theory, a heterogeneous engineer has a utility in developing and uniting a laboratory around the vision of the 'next big machine'. The discussion section below considers this issue in more detail. Table 3 comprises a summary of the characteristics of leaders in megascience projects:

Characteristic	**Restrictions**
Technical competence	Essential for all leaders at all levels
Team empowerment	Important for all leaders
Trustworthiness	Essential for all leaders and their teams, links to team empowerment
Charisma	Important at all levels
Management ability	Observed at all levels but essential for middle managers especially towards the end stages of a project
Vision	Essential for first senior leader, less important for subsequent senior leaders. Redundant for leaders elsewhere
Guided democracy	Only observed amongst leaders within experimental collaborations

Table 3: A summary of the characteristics of leaders in megascience projects and the nature of any restrictions on where these characteristics were observed

Discussion

The original expectation when conducting the literature review portion of this research was that the fieldwork would provide an opportunity to expand the heterogeneous engineer concept beyond Carlo Rubbia and use it as a framework for a broader understanding of leadership in megascience projects. If this were to be the case, one might expect the interviewees to describe several individuals as taking direct control over project resources and displaying significant authoritarian and transformational leadership characteristics. However, the general characteristics of these leaders was far more democratic. The interviewees even described Carlo Rubbia as an anomalous leader within science, for exercising such an authoritarian leadership style. While Rubbia is not unique amongst scientific leaders for exercising an authoritarian leadership style – for example Samuel Ting has also been described by the literature in authoritarian terms (Riordan *et al.*, 2015), Nonetheless, Rubbia's leadership was regarded as a necessary evil for CERN both during the period that Krige (2001) described and the LHC era. During the fieldwork, one potential heterogeneous engineer emerged – Robert Wilson of Fermilab. During the conception and launch of the laboratory, the interviewees described Wilson as taking a direct role in very detailed technical decisions. This also occurred during the Tevatron era. These decisions even needed amendment by others to make them technically feasible as noted above. However, as with Rubbia, the interviewees considered Wilson as a relative anomaly amongst scientists for his tendency to be involved in the most detailed technical decisions. While Wilson and Rubbia's ability to take direct control over all aspects of a project or laboratory was a useful tool at early project stages, they were inappropriate for the later phases of the project's lifecycle. The laboratory subsequently brought in a new senior leader who could meet the changing needs of the project. In these cases, Rubbia and Wilson were succeeded by Christopher Llewellyn-Smith and Leon Lederman respectively, each of whom built agreement with external partners to build the machine (Hoddeson and Kolb, 2003; Smith, 2007).

While the project leaders and managers for the Tevatron and LHC had the discretion to be more authoritarian if needed, leaders within experimental collaborations generally exercised a far more democratic leadership style. This is partly a product of the funding arrangements where 80% of LHC funds are controlled centrally whereas 80% of funds for ATLAS and CMS are controlled by individual researchers(Eggleton, 2017). Yet, as Rubbia came from an experimental background one might expect him to embody this democratic style. This was not in evidence. One might therefore reasonably ask why an anomalous leader should emerge and why the experimentalist community would allow such a leader to exercise so much control over themselves. Interviewee comments indicate that in certain situations, such as a crisis or an ongoing period of stagnation, an experimental collaboration might give up its traditional autonomy to an authoritarian leader who could take the unpopular but necessary decisions to secure good scientific outcomes.

Although there is a work of literature looking at very charismatic individuals with several conceptual frameworks examining them (Galton, 1869; Law, 1987b; Joerges, 1996; Krige, 2001), these examine certain anomalous individuals. These conceptual frameworks are not directly relevant for a broader understanding of leadership in megascience projects. While there is value is considering edge cases, one must also remember that heroes and heroines are relatively rare. This indicates the future research in this field should consider analysing leadership using leader-member exchange concepts (Graen *et al.*, 1982; Graen and Uhl-Bien, 1995). Leader member exchange considers leadership to be a dynamic process between leader and follower, and both parties can influence what types of leadership are considered reasonable (Graen *et al.*, 1982). This will inevitably impact the leadership training programmes for research infrastructures identified in the introduction (Paterson *et al*., 2017). By treating leadership as a participatory process between leader and follower rather than focussing on a single individual's skills, there will need to be greater emphasis on training leaders in understanding and facilitating team dynamics. This is much more challenging to train than a more leadership curriculum, but trainees will get greater value from such insight.

In summary, the characteristics of leaders in megascience projects tend towards technical competence and trust. Although there are several other characteristics, these two ultimately hold the entire endeavour together. This is true irrespective of whether the project is accelerator construction or an experimental collaboration.

Conclusion and theoretical implications

What has emerged is the nature of leadership within these megascience projects, namely a relatively authoritarian accelerator construction community and a far more democratic community of experimental collaborators. These findings indicate that while scientists have often argued of the uniqueness of scientific work to justify special treatment, this is not entirely the reality. Rather the construction of apparatus is rather more similar to other kinds of megaproject with a few additional quirks such as the issue of technological uncertainty. The evidence therefore indicates that the heterogeneous engineer is an inappropriate conceptual framework for developing broader leadership theory in scientific projects. Krige (2001) developed the concept of the heterogeneous engineer based on an individual who has emerged to be a relative anomaly both within experimental collaborations and within scientific projects more broadly. While the heterogeneous engineer is not restricted to a lone individual, with at least two other potential candidates emerging during this research, such individuals are considered exceptions to the general leadership norms which were also identified in this paper (Liyanage and Boisot, 2011). Such heterogeneous engineers, who bear significant similarities to authoritarian leadership styles (Bass, 1990), are also not considered to be bad for science and in fact have utility in early project or experimental scenarios.

There are justifications for using these findings to pursue two potential new research trajectories. The first is to conduct further work towards understanding the nature of these heterogeneous engineers. Such individuals are relative anomalies within scientific work and there is considerable academic value in understanding unusual cases. In particular, their roles in the early stages of a new project or new laboratory indicates that developing understandings in this area would be of interest to both scholars and laboratory stakeholders for strategy. The second potential research trajectory is to examine the role of the heterogeneous engineer as a specific component of laboratory strategy. After the heterogeneous engineer had secured the future of the machine within strategy, a different leader was substituted to meet the new needs of the project. Future work should examine this strategy in more detail, perhaps expanding the study to include more projects.

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