The Large Hadron Collider

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Executive Summary: The Large Hadron Collider Project

In this report, we analyse the project management techniques used in the planning and construction of the Large Hadron Collider (or LHC) by CERN. The extreme scale of such a project, coupled with its scientific nature, make this both a fascinating case study and a good example of how traditional project management techniques do need adapting to fit some unusual projects.

First envisioned in 1977, the LHC project was intended to increase the energy imparted to collided particles to 1 TeV (Tera-electron-Volt). The use of Hadron collisions was deemed the only practical way of achieving this goal. At least initially, the project was championed by Nobel Prize winning physicist Carlo Rubbia, who staunchly promoted the project, which was approved shortly after his ascension to Director General of CERN.

Due to the LHC's nature as a scientific project, it was not expected to bring in any revenue directly. This means that the Triple Bottom Line model does not directly apply: there is no financial bottom-line. Furthermore, as scientific progress is by nature unpredictable: a "scientific bottom-line" would be impossible to correctly predict. Furthermore, this renders Return On Investment modelling very difficult, completely discounting the possibility of using Quantitative measurement. While CERN did take cursory consideration of the environmental and societal impact of the project, these were by no means exhaustive.

The LHC deviates from the project lifecycle model in a couple of ways: most notably – due to the duration of the project – much of the concept and planning phase had to be extended in order to accommodate changing technological and political situations. Much of the concept and planning work occurred concurrently, as without some of the more detailed plans, CERN were unsure of the project's feasibility. Furthermore, due to the large number of components which were required by the project – and the desire to use technology which had not yet appeared at the time of the project's conception – much of the detailed planning was interleaved with the execution phase.

Midway through the project – during the execution phase – CERN found that the existing systems (both in-place at CERN and commercially available) for monitoring and managing the project during its construction were inadequate for their environment. At this (somewhat late) stage of the project, a new system was developed internally: the Earned Value Management System (EVM).

Amongst the changes to the management of the LHC project, the most important we would make are including more people trained in project management – the bulk of the project was managed by physicists – and to split the project up into smaller sub-projects which could be better managed (using the Project Lifecycle method) individually.

Contents

1 Part A) Case Study

1.1 Concept

While CERN's earliest concepts for a Large Hadron Collider can be traced back to 1977[1 2], the detailed planning for the project began in 1995. Thus, under the Project Lifecycle model, the extended Concept Phase ran for almost 2 decades. This is partially explained by the project having not been formally approved until the presentation of the equivalent of a project charter in 1994, [3] after much work had already been carried out.[4 5 6].

Even in 1977 – with the first plans only beginning to hatch – it was proposed to build the LHC in the Large Electron Positron Collider (LEP) tunnel after the LEP experiments were brought to a close. The LEP had only just been completed in 1975[1]. A Feasibility Study was conducted in 1984 [3]. In 1987, the LHC was almost canned, as the Superconducting Super Collider (SSC) was approved in the US, however Nobel Prize winner Carlo Rubbia continued to push for it[1]. He claimed it would be a much higher quality collider (predicting higher Luminosity) than the SSC [1], He also suggested it would be more versatile and able to collide heavy ions as well as Hadrons[3 6]. Rubbia became the Director General of CERN in 1989[1]. In 1993, the SSC was terminated due to costing mistakes: the expected cost had been revised from $4.4 billion to over $11 billion[3].

In the Concept stage of the LHC project there were two major meetings of CERN Council: the 1991 meeting where the project was proposed and the 1994 meeting where the project was approved after the presentation of a document similar to a Project Charter.

The project was initially presented to the CERN Council, in 1991[5]. The goal presented was: For the advancement of high energy particle physics, there is a need to study constituent collisions at energies of greater than 1TeV.[7] The constituent energy (energy imparted onto the subparticles of those collided) was calculated to be about 10% of the particle energy. It was deemed that – due to the technological constraints of the time – the only way to do this in the next 10 years was with Hadron Collisions [7]. After discussion of other options, it was agreed that "In all these respects (advancement of science, nature of machine, preliminary costs estimates), the LHC is the right machine for the advancement of the subject and the future of CERN"[8].

The triple bottom line considerations discussed in 1991 were:

- Environmental
  - There will be no direct effect from the experiments that will eventually be carried out on the environment. Radiation will extremely low at ground level: not detectable above background. The LHC will be sufficiently well shielded to minimize radiation leaks [6].
  - The LHC will be more energy efficient than the existing Super Proton Synchrotron (SPS), which was CERN's main hadron collider as the time. Yearly energy consumption "remarkably small considering enhancement it brings to physics": 25 times the collision energy and 10 000 luminosity at the same power usage. [6]
- Social
  - Having particle accelerators was considered an important part of the European cultural identity.[5]

- Financial
    - Funded at present budgetary level, but additional contributions should be encouraged with industrial incentives. Non-member contributions can accepted in work or in cash. [7]
    - Extremely cost effective as using previous investments in civil engineering (LEP tunnel), and Injector Accelerators (the SSP).[7]

The Director General was asked to provide more details on

- final costs,
- technical feasibility,
- involvement of stakeholders (member and non-member states),
- final experimental use, with regard to
    - goals;
    - Ongoing direct costs to CERN;
    - Indirect cost to other stakeholder.

and other factors to the Council in 1993 [8] In 1994 CERN Council discussed these recommendations, which basically formed a project charter. [3]

The project charter-like document "The Large Hadron Collider Project" – hereafter referred to as the Project Charter for brevity – was presented in 1994. It included of a summary of 9 documents which had been presented over the prior 6 months [3], covering:

- background information on CERN, and particle physics in general;
- semi-detailed designs for the machine;
- the experimental program once the machine was completed, including costings;
- cost estimates (2230 Million Swiss Francs at 1993 value) and funding.

This document also discussed the stakeholders: CERN, member-states, non-member states, the International Committee for Future Accelerators (ICFA) and scientists across the world [9]. It gave consideration to the impact of the project on CERN's other experiments and the requirement to shut down and diminish other venues to secure the resources [9]. The major risks considered were budgetary and personnel. Alternate timelines were developed based on potential funding level. The document further warned of the risks associated with CERN's large number of employees expected to retire before the machines complete [9]. The Project Charter emphasized the need for rapid approval. The resolution to go ahead was passed at that meeting, subject to detailed review in 1997 [1 9].

1.2 Planning

The planning phase of the Large Hadron Collider project started as early as 1995. Given the complexity and scale of the project, a variety of special considerations had to be made when formulating the planning process. Specifically,

- The time horizon of the project was long (multiple years) and consisted of multiple phases;
- The chain of command was complex and consisted of multiple teams;
- The project dealt with cutting-edge technology and there was a high degree of specialisation within the teams;

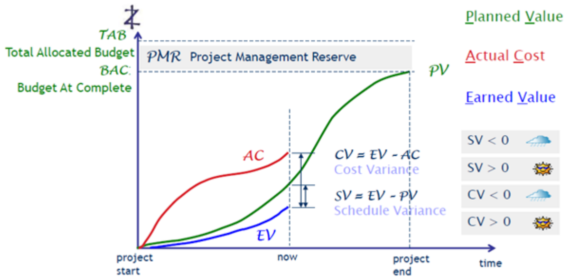
- The project required coordination of a large number of people across multiple countries [10].

These factors meant that extra care had to be taken in the planning phase to ensure the project would go smoothly. Primarily, communication and coordination were crucial, and the various sources of risk had to be carefully managed.[10]

To effectively deal with these complex factors, a series of planning techniques was implemented. This included a focus on deliverables and Work Units (WU) to split and measure work progress, as well as the use of multi-level planning.[10] Product Breakdown Structures, Assembly Breakdown Structures, and Work Breakdown Structures were all prepared, and regular reporting was utilized to ensure the project stayed on schedule.[11][12] Qualitative risk analysis was used to assess each risk [11]. Three different schedules were prepared, each with varying levels of detail about project stages, consistent with their multi-level planning model.[11] However, the planning process merged together with the execution phase throughout the project due to the long time frame of the project as a whole.

1.3 Execution

The execution stage of the project involved important monitoring and controlling process to keep on time, in budget and allocate resources efficiently. The most important system used to monitor and control the project was the EVM system. In order to ensure a formal process for tracking progress, in 2001 CERN created a new EVM (Earned Value Management) system, to replace the failed Excel-based system they were using.[13] Existing systems were inadequate for CERN's unique environment for technical reasons, requiring the development of such a new, targeted system. The EVM system is built around the concept of the Work Breakdown Structure (WBS).Tasks are broken down into work units, whose progress would be tracked by the individuals working on them. Expenditure was tracked and plotted against time in an S-curve to monitor progress. [13][14] The system was designed to be compliant with ANSI #748, though it moves beyond the standard where required by the LHC project.



This diagram illustrates EVM [15]. It is possible to monitor the cost variance and the schedule variance with what was planned.

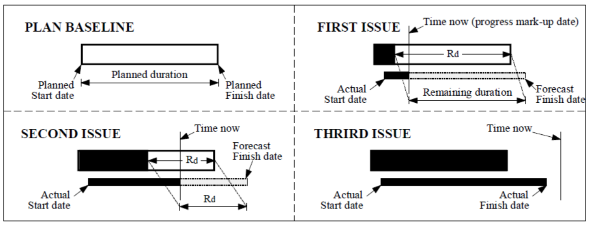
Due to the number of international stakeholders in the LHC project, it was very important that there were regular, detailed reports for the public. An annual report was issued [14] containing a detailed analysis of the project's project so far. In the report, in the executive summary, it detailed the current financial, technical, scheduling and other issues in a simple way to be presented to important overview committees and councils. The scheduling systems are described in detail in the planning stage. Scheduling was monitored during the execution stage. To fix scheduling problems there was comprehensive monitoring processes including weekly planning meetings and a paperwork process to make changes.

The progress reports' purpose was to depict the actual status of the project and to compare it to the planned progress. There are three measures of progress report, which are: time progress report, physical and worked time progress report found in annual and monthly progress reports[11].

1.3.1 Time progress report

This report is for recording time elapsed and remaining for each task and applied for master and coordination schedules. The procedure of making the report is as follows:[11]

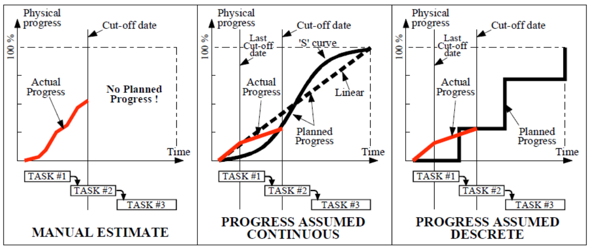
Physical and worked time progress report The physical and worked time progress reports were designed to enable users to evaluate the performance of the project and to see the overall progress. The principle behind the progress estimation was to allocate progress values to individual milestones. There are many ways to assess the physical progress between milestones: for example, by manual estimation of the progress, by assuming linear or Gaussian progress between milestone or by assuming there is no change in progress between milestones. The figure below is to help show the differences.[11] Physical and worked time progress report The physical and worked time progress reports were designed to enable users to evaluate the performance of the project and to see the overall progress. The principle behind the progress estimation was to allocate progress values to individual milestones. There are many ways to assess the physical progress between milestones: for example, by manual estimation of the progress, by assuming linear or Gaussian progress between milestone or by assuming there is no change in progress between milestones. The figure below is to help show the differences.[11]



Marking up progress

1.3.2 Physical and worked time progress report

The physical and worked time progress reports were designed to enable users to evaluate the performance of the project and to see the overall progress. The principle behind the progress estimation was to allocate progress values to individual milestones. There are many ways to assess the physical progress between milestones: for example, by manual estimation of the progress, by assuming linear or Gaussian progress between milestone or by assuming there is no change in progress between milestones. The figure below is to help show the differences.[11]



Physical progress assessment

1.3.3 Monthly progress report

The monthly progress report was designated to record the works which has been achieved in the period both qualitatively and quantitatively: what (if any) problems appeared, their consequences and actions taken to resolve the problem as well as the real status of the project compared to the project plan. [11]

2 Part B) Critically Analyse the Key Project Management Stages

2.1 Concept

2.1.1 Project Selection

The project selection criteria used were necessarily rather different from those used in a commercial venture. In particular, the quantitative measures such as return on investment are not directly applicable as the project makes no financial profit. The qualitative measures remain the same, though there is much less emphasis on competition in the scientific community: any advances are shared, though there is a certain pride taken in discovery.

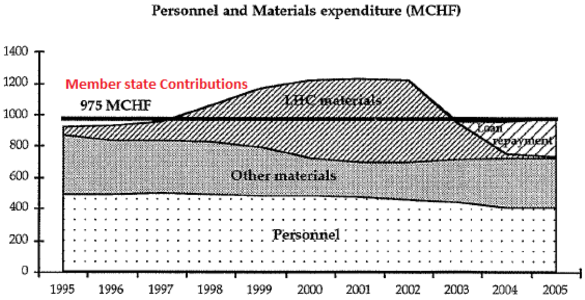
Qualitative Measures Used For Project Selection Early in the LHC project's concept phase – 1984-1994 – it was largely kept going as a "sacred cow" of Carlo Rubbia, who became the CERN Director General in 1989 [1]. This can be seen in his presentation to CERN council in 1991 [7] which got the initial approval for him to organise the drafting of the Project Charter. Even prior to becoming the Director General, Carlo Rubbia had considerable influence within CERN as a Nobel prize winner in the field of particle physics [1] [2].

Brief consideration was given to the competitive advantage: to keep Europe on the forefront of experimental physics [5]. However, this was not given much consideration as the international scale of the project was so great [14]. Indeed the project was almost stopped in 1987, out of desire not to compete with the US SSC [1]. The increasing awareness of the international scope of the project is reflected in the original proposal in 1991 taking great consideration for the European Committee for Future Accelerators (ECFA) [5], whereas by 1994 the Project Charter instead looks to the International Committee for Future Accelerators (ICFA) [3]. Competitive advantage was not a major influence in the selection of the project.

Some examination was done to determine the comparative benefit of other machines that could allow the required 1 TeV constituent collisions. One such consideration was a Super Large Electron Positron Collider (Super LEP). It was found that the cost of a Super LEP would be quadratically related to the energy it could deliver, and was thus untenable [5]. Very strong emphasis was given to the LHC being the only machine that could deliver this goal with current technology [5].

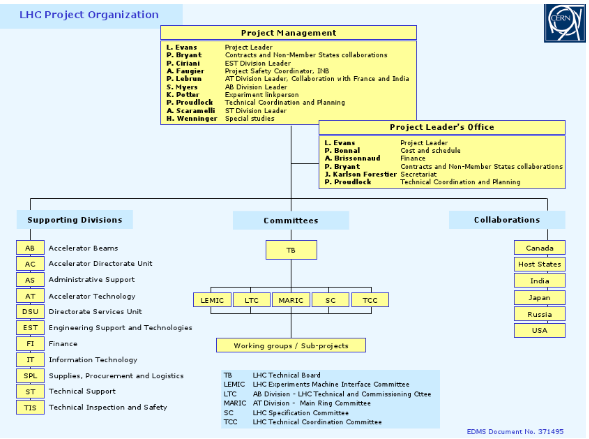
Quantitative Measures Used For Project Selection Rather than considering how long it will take the profits from the LHC to pay for it, (ROI), instead CERN considers the time taken for its external funding to allow for the payment. The LHC delivers no direct financial profits, so cannot pay for itself.

In the Project Charter the expected costs were outlined [3]. Extensive costing estimates were done in 1993, though the precise details of these administrative records are sealed for 30 years [16]. Most cost estimates in the charter were done in Millions of Swiss Francs (MCHF) at the 1993 level, though some were scaled in line with Net Present Value measures[17] taking into account price differences in 1994 [3]. Below is shown the total projected expenses of CERN, compared to the member state contributions.



We can see the gradual decrease in personnel costs, as CERN intended to cut down on its employees [3]. We also see the sharp decline of the "Other Materials" costs; CERN was required by the plan to shut down many of its other venues to fund the LHC. This graph also highlights to the reader that CERN will be unable to pay back all the debt created between 1994 and 2003 before the end of the timeline. This brought to the attention of CERN council the need to consider other funding options, which were brought forth in the charter [3].

2.1.2 Project Management Structure



Project Management	
L. Evans	Project Leader
P. Bryant	Contracts and Non-Member States collaborations
P. Ciriani	EST Division Leader
A. Faugier	Project Safety Coordinator, INB
P. Lebrun	AT Division Leader, Collaboration with France and India
S. Myers	AB Division Leader
K. Potter	Experiment linkperson
P. Proudlock	Technical Coordination and Planning
A. Scaramelli	ST Division Leader
H. Wenninger	Special studies

Project Leader's Office	
L. Evans	Project Leader
P. Bonnal	Cost and schedule
A. Brissonnaud	Finance
P. Bryant	Contracts and Non-Member States collaborations
J. Karlson Forestier	Secretariat
P. Proudlock	Technical Coordination and Planning

Supporting Divisions	
AB	Accelerator Beams
AC	Accelerator Directorate Unit
AS	Administrative Support
AT	Accelerator Technology
DSU	Directorate Services Unit
EST	Engineering Support and Technologies
FI	Finance
IT	Information Technology
SPL	Supplies, Procurement and Logistics
ST	Technical Support
TIS	Technical Inspection and Safety

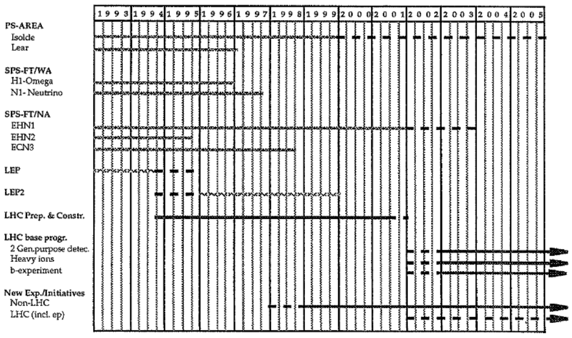
TB	LHC Technical Board
LEMIC	LHC Experiments Machine Interface Committee
LTC	AB Division - LHC Technical and Commissioning Cttee
MARIC	AT Division - Main Ring Committee
SC	LHC Specification Committee
TCC	LHC Technical Coordination Committee

Above: Project Organization Chart, showing boards of governance, and project leaders [18]

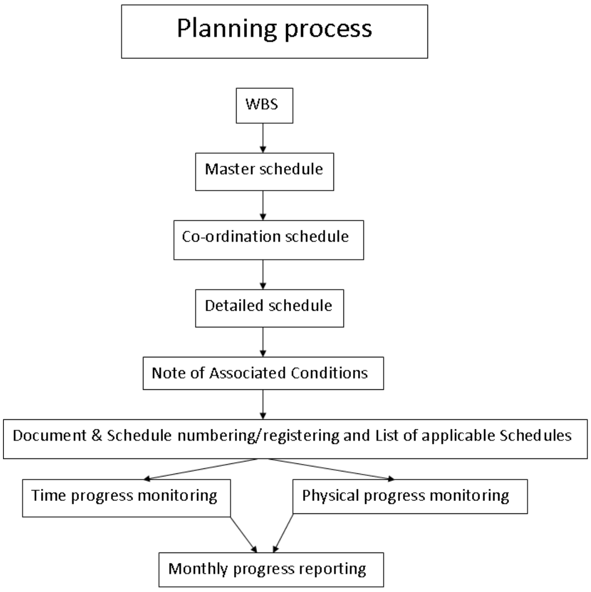
A project of this immense scale requires vast oversight and organization. Where a typical "large" project might have had a cost in the hundreds of thousands, or even millions of dollars, [17] the LHC's cost was measured in the billions. A "large" project might typically have had a time frame measured in months [17]; the LHC had a lead-time measured in decades. So whereas a "large" project might have had a full time project manager or two and a steering committee [17]; the LHC had dozens of project managers, and 6 steering committees [18]. The project organisation chart from 2003 is displayed above and was continually updated as the project's needs evolved [18]. This clear identification of roles was crucial in the deliverance of the benefits of governance [17].

2.1.3 Timing

Much effort went to the positioning of the LHC within the structure of experimental programs at CERN. Since it was to be built out of the LEP tunnel, all LEP experiments needed to be completed before construction on the SPS[8] as an injector, which was itself connected to the Proton Synchrotron (PS), there would be large interruption to the use of many of its venues [3]. This is combined with the need to decrease other expenditures, and thus the closure of some experiments such as the Low Energy Antiproton Ring (LEAR). To give a big picture overview a Gantt chart was produced, detailing all affected programs [3] (below). It was acknowledged as an ideal, and that a 2 year delay was likely before the LHC was up and running [3]



2.2 Planning



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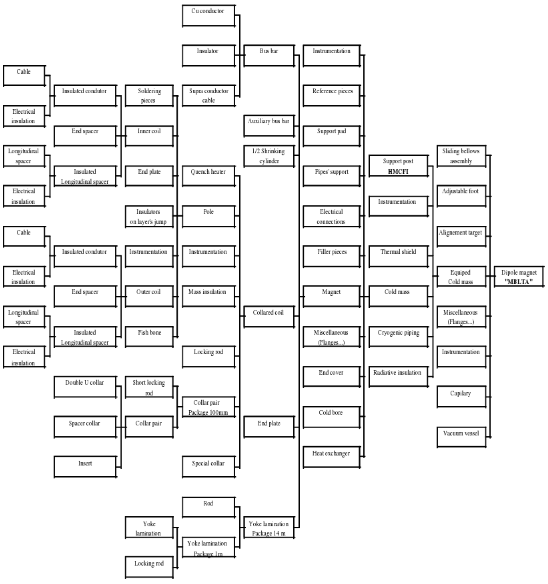
2.2.1 Work Breakdown Structure

Before detailed planning can occur it is necessary to prepare a work breakdown structure to define the work that needs to be done, and to do this the product breakdown structure and assembly breakdown structure must first be constructed.

The product breakdown structure consists of:

- A product tree describing the complete configuration of the LHC;
- Instructions on manufacturing, machining, quality control etc. for each level and branch of the product structure, and
- Technical description of the elementary parts, i.e. the leaves, of the product structure.[12]

An example of a draft PBS for the installation of the dipole cryomagnets is included below.[12]

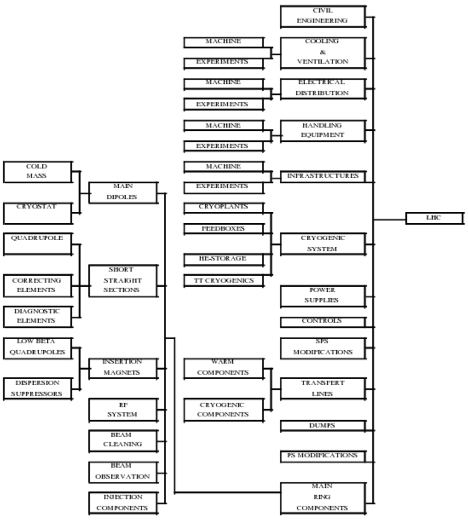


Preparing the PBS required management staff to identify each component and part of the LHC; including manufacturing, assembly and quality control information in each branch of the PBS; and to further develop rules of design and control to minimize risk in later stages of the project. They were also required to authorise and conduct the collection of product information and to create a database in which to store and manage it.

Next, the assembly breakdown structure must be prepared, which consists of:

- A description of the time related sequence of activities needed to be taken to complete the project
- Part and activity related information that alter the original assembly sequence given by the PBS
- Other information related to the activities and the site, which influence the WBS development

A draft ABS is included below.[12]



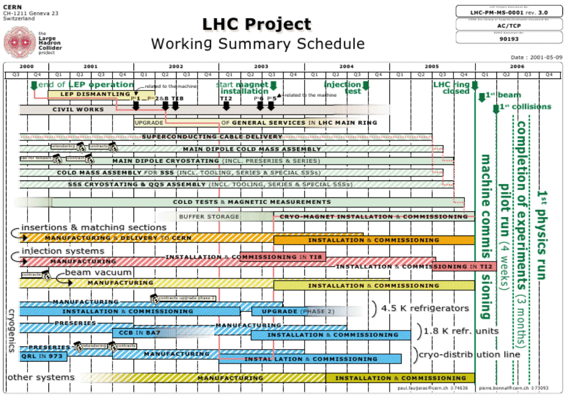
A draft ABS for the LHC.

LHC, and compliment the PBS with information about installation tasks.

These are both used in the construction of the overarching Work Breakdown Structure. It outlines a list of specific work units needed to complete a specific process or job, owned by the planning coordinators. These work units:

1. have one or more objectives
2. act as control points along with specific criteria for evaluating performance
3. have known requirements of money, labour and other resources
4. have a named individual responsible for the outcome
5. have a relatively short life of about two months, maximum three[11][10]

In addition, Gantt charts and resource allocation schedules were also prepared. A copy of the working summary schedule used is detailed below.[19]



2.2.2 Multi-level planning

Multi-level planning is used and there are general requirement applied for every schedule, which are:

- All of the schedule are to be marked-up weekly with Actual/Expected start and finish Dates and be issued as Detailed Progress Mark-up Schedules. The frequency depends on the type of schedule, weekly for Detailed schedule and monthly for both Master and Coordination schedule
- Shows the time span and Milestone of the project (when adequate)
- Be presented in form of Gantt chart
- Follow the Gantt chart, symbol, bar color/pattern code
- The higher level schedules should be consistent with the tasks, Time Spans, and Milestones dates contained in the lower level schedule.
- Both Coordination and Detailed schedules shall be established using network (precedence method) and resource analysis, in a sufficient detail to demonstrate the logic and viability of the schedules. [9]

Level 0 - Summary schedule A Gantt chart consist of 100 tasks shall be derived by rolling up the Master schedule. [9]

Level 1 - Master schedule The master schedule is issued by the planning coordinators together with the schedule note at the beginning of the project. It is prepared by planning coordinator and approved by project management, before being used to assess progress of the project and communication outside project team.[11]

There are five Gantt charts and no more than 150 tasks in each schedule. The master schedule covers the whole project from prototyping to commissioning. It also shows the duration of the main tasks down to level 2 of the Product Breakdown and Generic Activity Structures: highlighting the critical paths. [9]

Level 2 - Coordination schedule The coordination schedule is issued to key staff at early stage of each major phases (e.g. design, procurement, manufacturing, etc.) in form of five Gantt charts and consists of no more than 300 tasks each[11] [9]. It is prepared by Planning Co-ordinator and verified by Technical group before being approved by Project Management. When formally approved, It can be given to suppliers and sub-contractors.[11]

The schedule covers many things including R&D (prototyping) and Design, Tendering and Contracting (purchase orders and construction/installation contracts), Manufacturing : from tooling up to series production and delivery to CERN, Construction and Installation, Tests and Commissioning. It shows relevance Interface Dates and detailed down to Work Units. Also, the schedule shows highlight of critical paths and utilises early start and early finish dates to identify floats. [9]

Level 3 Detailed schedule The detailed schedule purposes are to show resources required to achieve task available and to show the work is feasible in the time available. It is prepared by either planning coordinator or technical groups, verified by technical groups and approved by a planning coordinator before being issued by the technical croup planners at the early stage of the phase, together with a “schedule note”. It important to notice that the schedule is only prepared for the immediate future (to cover maximum of 4 months.)[11]

The schedule covers the whole duration of a Work Unit or a group of Work Units (Work Package). It shows relevant Interface Dates be detailed down to elementary tasks. [9]

2.2.3 Risk Analysis

To manage the various sources of risks, there are two methods of risk analysis that can be used: qualitative and quantitative. For speculative R&D projects such as the LHC, quantitative methods are costly and produced limited results. For this reason, qualitative analysis was employed, where the risks were identified at each stage of the project. Multiple scenarios were simulated, schedules were created based on these scenarios and the risks were analysed accordingly. [9]

At the beginning of the project, the details of all the work units, some of which would not start for ten years, was not known. [9] This meant that the WBS and schedules had to be periodically reviewed, and new work units added as necessary. This is a unique problem with large time-period projects like the LHC, where the planning phase cannot necessarily be completed before the execution phase. As will be explained later in this report, this caused a number of problems during the execution phase and resulted in long delays in installation and cost blowouts.

2.3 Execution and Monitoring

For such a large-scale project the execution stage of the LHC project was reasonably successful. However, there were some significant project management problems which were partly responsible for time, cost, specification and resources problems.

The most significant problem with the project management system was identified during the execution stage in a 2001 Audit [20]. Initially, budgeting and cost control was the responsibility of the LHC Project Administrator and Technical Planning and Scheduling was under the LHC Project Technical Coordinator. There were no links between the excel-based cost packages and work packages. During the 2001 audit the Technical Coordinator identified that the project was behind schedule and the Project Administrator identified the project was under-running. The project was also found to have had a cost blowout of 330 million Euros. This blowout meant that the completion date was pushed back from 2005 to 2007. The project management team was not able to show that the Estimate At Completion (EAC) was less than the Total Allocated Budget (TAB). The CERN Member states asked LHC Project Management to implement a project control system which became the deliverable-oriented EVMS. The problems with the initial cost and schedule systems were so significant that they had to be changed midway through the execution phase. The new project control system combined measurements of schedule, cost and specification. However, there were still problems with this new system.

The EVMS did not capture future extra costs identified due to problems with civil engineering, contractors and integration. The extra costs had to be absorbed by other savings through a 'call on contingency' process. Other problems identified by Bonnal [20] with the EVMS were the varying granularity of projects – from kCHF (Thousands of Swiss Francs) to MCHF (Millions of Swiss Francs) and a few days to a few months – too many activities (12000) for humans to get on top of, the planned budgets being 'too optimistic' and weak integrations with schedule networks. These problems with the EVMS occurred because activities were put into the EVMS system without any consideration for the managers and departments that had to make sense of all of them. Due to the aforementioned technical problems, the schedules were changed regularly through a comprehensive monitoring processes. Even though it was possible to move around the scheduling to keep to the important milestones throughout the project, it was not ideal to have to change schedule regularly. The changes made pointed to a problem with planning of budgets for contingencies, underestimating the risks of contracts, a shortage of integration studies and a shortage of staffing and availability of transport and handling [14]. These factors may have been overlooked by project management or simply re-prioritized to fit the lean budgeting for the project. Another problem that occurred with the project management in the execution stage was the sheer volume of the databases that accumulated. In 2005 safety was compromised when a load fell on a worker and killed him. This pointed to a big problem in their safety systems management.

2.4 Finalisation

Finalisation in regards to the LHC project was not done especially formally due to the staged and modular approach of the project. Many of the aspects typically present in the finalisation phase occurred alongside the long execution phase of the project, such as the distribution and closing of individual work contracts and the continuous auditing that took place.

Auditing and review took place both internally and externally and at the very least there was one scheduled review of the project annually. These audits focused on technical and cost-to-completion issues as well as the managerial and resource-management aspects of the project [21].

One such audit by the US department of energy found that cost estimations for the LHC were reasonable and based upon CERN's existing experience, technical expertise, infrastructure and existing accelerator systems. Construction schedules appeared feasible – assuming funding goals could be met – and that there was considerable flexibility in the deployment of resources. The committee found that the project had experienced, technically knowledgeable and well-functioning management systems in place complemented by a formal scheduling system philosophy including the use of scheduling software packages [22]. Due to the high level of technical expertise required in the field, and the fact that much of this expertise was already concentrated at CERN, it is difficult to say just how effective and accurate the audits were at their time of completion. From a post-project standpoint however the LHC did manage to achieve its goals with the necessary amount of funding and the technical knowledge that they had acquired.

Following the completion of the LHC and the commencement of the experiments, a worldwide LHC computing grid was designed and deployed in order to handle all the data of the LHC experiments. This system utilised a decentralised grid that is located in across 200 locations in many countries, providing the benefits of easy maintenance and upgrading of the systems due to local institution funding whilst still contributing to the global WLCG goals [23]. The main responsibilities of the WLCG are: safekeeping of raw data, distribution of raw data, large scale reprocessing, handling analysis and simulation event production and reconstruction [24].

In 2013 the LHC formally shut down to undergo future upgrades involving replacements of major accelerators and luminosity upgrades. The ultimate aim of the project is to achieve 14 TeV proton-proton collisions – a tenfold increase in luminosity. This project is scheduled for completion in 2015 and is known as CERN's Super Large Hadron Collider experiment (sLHC) [25].

Although the LHC project has formally finished, research utilising the LHC data and results is still ongoing. The LHC has greatly contributed to solving the fundamental issues of subatomic physics that arose in the 20th century: specifically the nature of subatomic forces, including discoveries in the behavioural differences of matter and antimatter and the discovery of a fourth quark; the 'charm quark'. The next frontier for the LHC and the upgraded sLHC is the origin of mass including the discovery of the Higgs Boson as predicted by the standard model of physics [26]. To this end, the LHC will continue conducting experiments which attempt to answer the following questions:

- What is the origin of mass of particles?
- Why is antimatter so rare?

- Do super-symmetrical particles exist?
- What is dark matter?
- Does space-time have more than four dimensions?

3 Part C) Recommendations

The LHC project did use the Project Lifecycle, however it was it was a deformed version of it.

A Lot of planning was done in the concept stage. A lot of risk analysis was done during the execution stage. Very little finalisation documentation was produced. We suggest a more rigorous following of the Project Life Cycle.

Triple Bottom line did not receive sufficient consideration. Partially this was because of the limited relevance of a financial bottom line. Even so this just highlights the importance of the environment and social bottom lines. Significantly more work needed to be done to consider the environmental and social impact of the project. Furthermore, despite the LHC not providing a direct financial return, the return in scientific knowledge was the primary goal of the project.

3.1 The Concept Stage

While the concept stage was very long, it did not do many of the tasks normally associated with the concept stage were not done. Very little concern given at a high level to

- Stakeholders other than those directly involved: Member and non-member states, the scientific community.
    - Even then very little detailed analysis carried out
        - This may have resulted in the early funding issues.[1] [2]
        - All stakeholders should have been identified in this stage[17]
            - to allow them to be engaged with as the project develops .[17]
        - Stakeholders, and the impacts on them should have been analysed using techniques such a rainbow charts, comparing the influence on the project, with the influence they have over it.
- The Social Bottom Line
    - Consideration was only given, to the impact on scientific society.
    - A specialised position on the governance board, or even the another board, should have been established in the concept stage to ensure this was covered.
- Environmental Bottom Line
    - We recommend again a specialised position on the governance board, or even an additional board be established to provide high level oversight to monitor environmental cost of the project as a whole.
- Risks.
    - Almost no consideration was given to the Risks.
    - To analyse the Risks in the Concept stage, techniques such
        - Brainstorming the Risks, to get a good overview.
        - Constructing Risk Matrices, with subject matter experts.

The concept stage was overly concerned with planning, we recommend the focus be shifted toward the consideration of risks, stakeholders, and the triple bottom line.

3.2 The Planning Stage

The planning phase of this project was poorly defined, and overlapped with the execution phase. For example, the first general coordination schedule was only constructed after civil engineering works had already started. [27] This was partly due to the nature of the project, being a speculative R&D project with a very long time horizon. The exact work and processes that needed to be conducted in the later stages of the project were largely unknown due to this long time horizon, leading to an overlapping of the planning process and the installation of the LHC. Risk analysis was also conducted in a similar manner.[11]

This was the cause of many problems in the execution stage. Miscommunication between project teams and inconsistencies between the master schedule and the coordination schedule caused the machine installation to be conducted before the integration and spatial studies, which caused long delays as the project could not proceed until the studies had been completed. [27] When technical problems arose in January 2004 during cryogenic line installation, the lack of a team dedicated to risk management meant that it caused major delays to the project [27]. The schedules were also found to be too optimistic in the face of these problems, which was a direct result of the way the schedules were constructed.

3.3 The Execution Stage:

Construction of the LHC proceeded before the systems were in place to properly monitor it. Due to the complexity of the project (and indeed the unique culture of CERN), many existing management tools were not deemed directly applicable. A new software product (the aforementioned EVM system) was developed, but was not introduced until midway through the project. In an ideal project, these problems should have been foreseen and solved before the execution phase began.

Furthermore, the detailed plans of some components of the project were not finished before the execution phase began.

The main paper that was conducted during the project concept stage in 1995 was by Bonnal [11]. In this paper they considered various systems to manage scheduling but no system had a method to monitor costs and resourcing against scheduling. Reading the paper it seems like they just didn't appreciate the scale of the project and how to manage so many different activities and contracts. Perhaps more thorough consultation with stakeholders and more investigation into literature on very large projects would have prevented the budget blowout and the miscommunicating that were identified in 2001.

Possible improvements to the EVM system that would have helped solve the problems identified in section B are to reduce and standardise the number of activities input into the EVMS. Bonnal [20] recommended to have <500 activities, most the activities in the range of 0.2-2% BAC, and duration of activities between 3months and 10% of overall project duration. The problem with standardizing the activities input into the EVMS is activities will be unnaturally augmented/diminished to fit the required size, some information on the activities may be lost, the individual groups completing these activities may not be happy being forced to standardize the size of their projects.

To overcome the scheduling problems with the

EVMS a number of recommendations were made in a paper by Barbero-Soto [27]. To solve contracting problems it recommends to split major contracts between two firms (diversify). To overcome technical issues, especially in the logistics area; perform spatial integration studies, setup special 'rescue' teams to deal with technical problems. These solutions have problems in themselves. The main problem is that these extra steps will cost money and there is a risk they may not be used during the project because scheduling problems don't arise.

The main solution for the problems with scheduling is to give the resources to allow contingency time in each of the stages of the project before the execution stage starts. This will avoid the costs of moving the schedule planning around during the execution stage. Allocating contingency time does include costs but the costs of doubling up schedules is greater than this in general.

3.4 The Finalisation Stage

A more formal finalisation process should have been adopted by CERN at the closing of the LHC project. Contracts and delegated works should have been officially concluded at the end of the project in addition to the stages of completion to ensure all work had been done.

Lack of documentation of lessons learned and best practices would prevent the tacit knowledge acquired to be easily transferred outside of CERN. Although much of the scientific community, especially in regards to particle colliders reside within CERN, it may be beneficial for purposes such as external auditing for expertise to exist without the organisation.

As a result the effectiveness of audits can be questionable as external organisations do not have the sufficient knowledge, or for a project of this scale, sufficient past examples to base their audits upon. And instead they often rely on the preconceived expectations they have of CERN.

3.5 Recommendations Conclusion

Many of the problems with the Project Management can be related to the use of technical people in management roles. The position of Project Manager was known as Senior Physicist. The Director General – and project champion – was a Nobel prize winning physicist [2]. The primary focus of these people was on the end goal. As could be seen even in the concept stage, the consideration was made for how the final experiments would be done, rather than on how the project was to be run [3]. We recommend that people with a stronger focus on – and more experience with – project management be included within the project. In particular, people with good knowledge of the Project Life Cycle and Triple Bottom Line should be put in management positions.

The main reason the Project Life Cycle was not adhered to was the long timescale of the project. This meant that the details of what needed to be done at each stage of the project were largely unknown before construction began. This lead to phases of the Life Cycle running into each other as concept, planning, and execution were all occurring at once. To ensure a more rigorous adherence of Life Cycle management, we recommend projects such as this should be conducted in stages: whereby each phase of the Life Cycle is applied to each stage in turn before moving on to the next stage. While this may make the project more expensive, it would ensure greater control and monitoring of the project at every stage, and reduce risk of problems during execution and subsequent delays.

4 Conclusion

The Large Hadron Collider is a very interesting project, quite atypical of engineering projects in many ways. With its colossal scale, many of the traditional project management techniques used broke down: it is difficult to plan a high-tech project decades before its completion. Furthermore, the LHC was not a for-profit enterprise, rather a scientific endeavour. This makes it very difficult to use quantitative methods for determining Return on Investment. Similarly, while any harm the project could have made to the environment was minimized, it is difficult to see any definite positive environmental effect; due to the very nature of science, exactly what will be discovered is an unknown. Societal impact is easier to measure in the short term: the LHC project will bring many scientists (and the occasional protester) to France and Switzerland. Ultimately, the LHC had too little focus on effective management – at least initially – and while the project went relatively smoothly, it would have been useful to have had these management systems from the beginning.

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