Evolution of Collaborative Engineering in Particle Physics Experiments

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Abstract

Particle Physics Experiments grow in number of Participants (> 1000), Participating Institutions (> 100), in size and above all in complexity. World-wide collaborative engineering based on subsidiarity and ease of communication is required. The preparation, construction, assembly, running-in and operation of such experiments spans more than 20 years, requiring an elaborate EDMS based on WWW.

Keywords: Distributed Engineering; EDMS; WWW for engineering information.

1 Introduction

Physics experiments at CERN have evolved and changed considerably over the past 20 years.

Experiments were mostly dedicated to very few or a single physics subjects using muon, neutrino, pion, hyperon, pbar and other specific beams at the Synchro Cyclotron (later the Booster), PS and SPS. Some of these experiments were realized by adding a specific "trigger" apparatus to a "facility" such as the 2 m bubble chamber, to BEPC, to Omega etc.

The ISR "collider" physics started in a similar way with very focused experiments aimed at particular features of the anticipated p-p collisions at the new energy domain of the ISR. However, in the ISR there were no specific beams pre-selecting the physics subjects nor the centre-of-mass movements focusing the physics into a small solid angle.

There was an early attempt of a facility, the SFM (Split Field Magnet) providing track and particle momentum information over a good part of the rapidity range to which specific triggers could be added. In the late years of the ISR the first attempt of a "general purpose" experiment aimed at extracting special physics subjects from a global understanding and analysis of all events occurring in the collisions of a particular machine was realized with the Open Axial Field Magnet and the corresponding experimental detector equipment.

The real first general purpose collider experiments were constructed for the $Sp\bar{p}$ S collider with the UA1 and UA2 experiments. The four large LEP experiments and the future LHC followed then in the same style. Such experiments record all events and by adding on-line or off-line selection criteria they single out events of higher interest. Today one "Higgs event" in ATLAS is expected to occur once in ~ 10^{15} collisions. The famous needle in the haystack is comparatively easy to find.

In Fig. 1 the evolution of the number of experiments, institutions and collaborating physicists is plotted over the last ~ 20 years. Many of the experiments were small with few institutions participating such as the Isolde and some of the R&D experiments and some are very large. The number of institutes participating has increased considerably over the last ~ 20 years as well as the number of participating physicists or users. Both do not yet seem to level off. Distinct increases mark the changes in the CERN programmes. The three plots also show how CERN turns more and more into a world-wide global institute of particle physics.

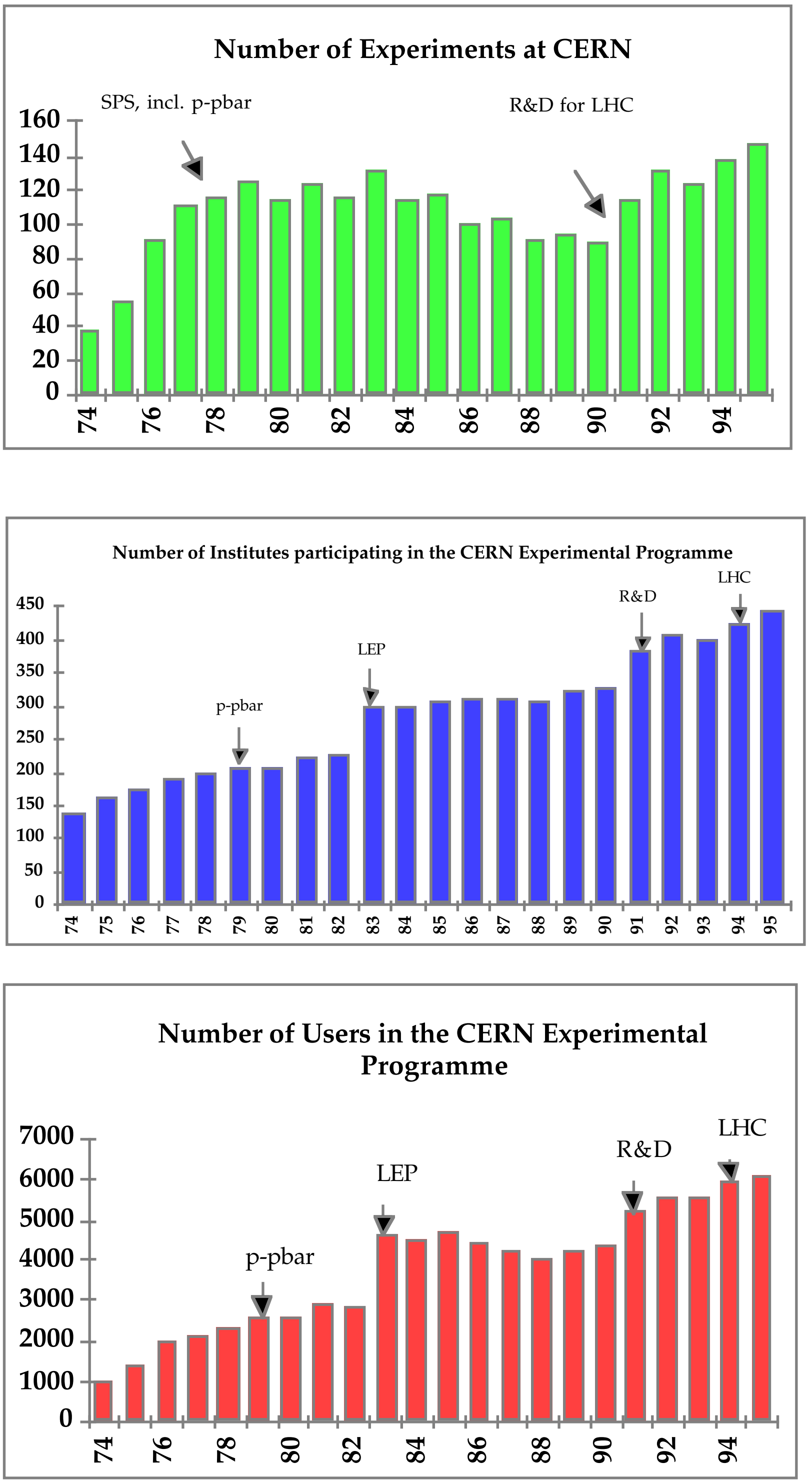

Figure 1: Number of experiments, institutes and users in the CERN experimental programme (source: "Experiments at CERN" 1974-1995))

1 ("Experiments at CERN" (Ref. 1) experiments are approved experiments which are either in preparation, data taking or analyzing; 1996 numbers: 96 experiments actively taking data; 315 Member State and 223 Non-Member State Institutes participating in CERN activities and 6687 experimental physicists doing at least part of their work with CERN)

The complexity, measured in number of channels, size and cost of the individual experiments is also evolving with time. In Table 1 indicative parameters are given for some typical experiments.

	1960	**1970**	**1980**	**1990**	**~ 2000**
Cost of typical large experiment/ facility (1993 prices)	200 MCHF (BEBC, Bubble Chamber)	60 MCHF (SFM/ISR)	70 MCHF (UA1, CDF)	100 MCHF (LEP, HERA SLD expts)	400 MCHF (LHC expts)
Number of users of experiment/ facility	600 (BEBC) 30/group	500 (SFM) 60/group	200 - 400	400 - 500	1000
Number of primary interactions used/sec	0.1 - 10^3	10^3 - 10^6 (ISR)	10^4 - 10^7	10^4 - 10^7 (HERA)	10^9
Spatial resolution of detector at a rate of:	60 micron 0.5 Hz	600 micron 1 MHz/ cm^2	100-200 micron 0.1MHz/ cm^2	10 micron 10 MHz/ cm^2	10 micron 100 MHz/ cm^2
Stored energy in magnets		750 M Joule (BEBC)		136 M Joule (ALEPH)	4 G JOULE (CMS)
Number of bits/sec digested	1-10^3 bit/sec	10^5 - 10^{10} bit/sec (SFM)	10^8 bit/sec (UA1)	10^{10} bit/sec (ALEPH)	$1*10^{16}$ bit/sec front-end
Number of detection channels	< 1000	10^3 - 10^5	5 * 10^4	5 * 10^5	2 * 10^8

Table 1: Performance increases of experiments and involved technologies

All CERN experiments were and are realized in a collaborative effort. The physicists and institutes involved in an idea work out a proposal which is submitted to an external peer review committee specific to the CERN programme considered (LHCC, LEPC, etc.) evaluating the physics interest, the feasibility, quality and appropriateness of the proposed apparatus and the technical capability of the collaborators to realise the apparatus.

Then the formal aspects of the collaborations like funding and the sharing of responsibilities for the construction of parts of the detector, common projects financed together in the collaboration, operation, maintenance and others are defined and detailed in a "Memorandum of Understanding". This is a document as close to a legal procedure as possible, but in effect a declaration of best intentions and efforts of all partners. The MoU is signed by the funding agencies supporting the collaborating institutes.

If recommended for approval by the specific committee and after establishing the MoU to an acceptable level, the CERN Research Board, chaired by the Director-General, then approves the experiment endorsing or updating the findings of the specific committee and agreeing to the formalities of the collaboration as detailed in the MoU.

This somewhat informal procedure has been operated successfully over many years with surprisingly good results, even for very large projects (100 MCHF). Particle Physics has made itself a name in realizing complex projects within predetermined schedules and budgets and we should add with distributed management and resources.

The essence of the success of constructing complex and expensive apparatus in such a light organizational form is the collaborative effort giving every institute involved the full responsibility to realize their share of the detector. The work is done in competition with other groups doing similar research and in a completely open exchange of know how on detector technology within the particle physics community. The producer and the customer are the same people.

A further important ingredient in constructing large complex detectors is the role of CERN as host institute.

With the increase of CERN users and activities the role of CERN changes. CERN, with respect to experiments, concentrates on technologies which are important for operating and maintaining experiments, and on key technologies, where the excellence and the resources of CERN are required.

CERN, however, also concentrates on co-ordination and integration tasks. In addition, CERN loses personnel at a rate of 1 - 2% per year since more than 10 years. To adapt to this, the composition of the CERN staff has changed dramatically over the past years (Fig. 2). Manual workers (Cat. 4) have been reduced by a factor of 2 - 3. Engineers and applied physicists still increase (Cat. 2). Research scientists (Cat. 1) are stable in numbers at a very low level (100 compared to many thousand users). Administrative staff decreases (Cat. 5).

The CERN Budget in buying power has remained constant over the last 20 years.

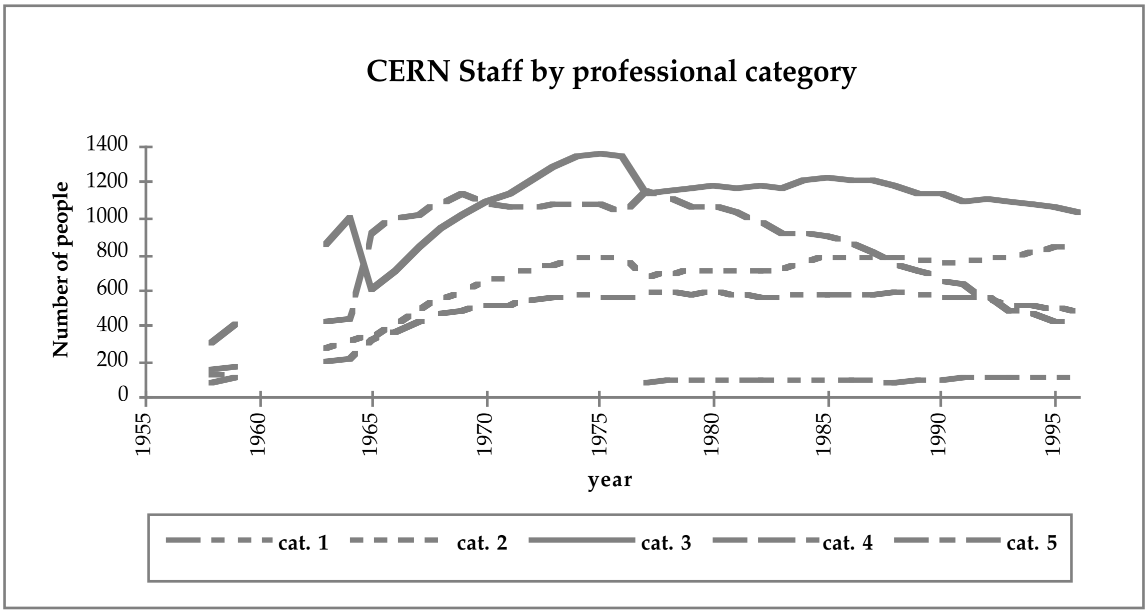

Figure 2: Evolution of CERN Staff Composition

In the following we shall investigate more closely the engineering efforts involved in constructing detectors and the corresponding informatic means which have evolved and made a common, coherent but distributed engineering possible, even of highly complex apparatus.

2 Evolution of the Engineering Organization

Typical large experiments around 1975 at the PS, the ISR and the SPS were collaborations of 5-10 institutes and 15-40 physicists. CERN Experimental Areas (PS, SPS) - or Experimental Support (ISR) - Groups provided for the engineering co-ordination and integration into the areas or machines backed by the engineering groups of the corresponding accelerator and research divisions. Specialised groups in the accelerators or experimental divisions developed, designed, tested and fabricated the more difficult components of the experiment such as magnets, wire chambers, Cerenkov counters and calorimeters. Other difficult apparatus was built in large regional centres such as RAL, CEA Saclay or other large HEP-Institutes.

A liaison physicist/engineer took care of the integration of the experiments into the corresponding machine. Together with a few physicists from the experiment they organized the engineering efforts. A strong participating CERN experimental group, consisting of research and applied physicists, mechanical and electronics engineers, was normally the backbone of the experimental team.

The CERN Track Chamber or later Experimental Facilities Division undertook the construction of very large bubble chamber facilities such as BEBC or the SFM magnet and array of proportional chambers seen as electronic bubble chamber.

Engineering tasks concern many fields and in the context of CERN mostly fields such as mechanical engineering, electronics design and electrical and fluids engineering. In the following the mechanical engineering will be taken as the main example and more specifically the electronics engineering tasks will not be described here since they do apply for more local phenomena in a detector.

Typically the main parts of the engineering tasks of these experiments were in the hands of CERN engineers and applied physicists who in turn relied on dedicated drawing offices and dedicated support groups. Drawings were made by hand on drawing boards and discussed in regular meetings organized by the liaison physicist or the engineer/physicist responsible for a subsystem.

Finite element calculations emerged as a necessary tool to design thin, transparent vacuum chambers and support structures for detectors. Where CERN was not responsible there were normally individual institutes organizing each complete subsystem.

Engineering work therefore proceeded in a clear-cut classical in-house engineering organisation with a minimum of boundaries and interfaces not handled exclusively by the institute in charge.

To give an example we can summarize the sharing of responsibilities for the large parts of the UA1 detector. The area and the movement arrangements of UA1, the magnets, the central track chamber and the data acquisition were CERN tasks. The barrel electromagnetic calorimeter was done by CEA/Saclay, the end-cap electromagnetic calorimeter by LAPP/Annecy and the hadron calorimeter by RAL. Excluding the area the CERN contribution was close to 50%. With only 3 external major partners the interfaces were simple. For all important co-ordination tasks meetings around a table were arranged at RAL, Saclay or CERN.

3 Engineering and the Technologies used

Particle physics experiments have to deal with a considerable mixture of technologies often approaching the limits of the state of the art: particle sensors of all kinds with associated electronics, high voltages in flammable gases within transparent vessels arranged to micron precision, ultra high vacuum in Be- or carbon fibre vacuum vessels, super conducting magnets integrated into liquid argon cryostats buried into thousands of tons of hadron calorimeters which in turn are positioned into a large super conducting spectrometer magnet filled with muon detectors. All of this has to be arranged 'hermetically' to catch all particles emanating from the collision. All of this has also to be connected with supports, cables services, safety devices, access means, moving gear, etc. Finally, all apparatus considered has an inflow of data from the front–end electronics in excess of $1*10^{16}$ bits/sec.

Team work is required to build a satisfactory detector where engineers must teach physicists to specify precisely what they really want and where physicists ask in turn the engineers to do much better than they thought possible.

4 Engineering and Simulation

For the purpose of understanding all features of the experimental apparatus a large number of calculations and simulations has to be done.

The original 'standard' collisions are simulated by producing hadronic and electronmagnetic cascades on as real a material distribution as possible. Magnetic fields must be known to a fraction of ‘per mille’precision for reconstruction of track momenta and for the understanding of details of electron movements in wire chambers.

Electric fields in precise mechanical boundaries are equally important to understand sampling processes in calorimeters and movements of electrons and ions in track detectors.

Radiation fields finally calculated in complex material environments need precise material properties, shapes and location in space. Such programs contain the cumulated knowledge of particle and nuclear physics in an energy range of TeV to KeV.

Interfaces from engineering drawings to such programs are being developed.

The first practical data exchange mechanism between GEANT and CAD packages exported data to EUCLID via SET (CAD INT), to be replaced by STEP (ISO 10303).

More work has to be done, especially on the case of transferring complex and complete CAD-3D geometries to the simulation packages. This requires help from the CERN Computing and Networks Division to organize common interfaces to transfer geometries (STEP!).

The final simulations used for understanding the detector must take fine details into account. The reason is the extraordinary selectivity of the apparatus required to identify the interesting physics events (1 in 10^{15} !!)

5 Particle Physics Detectors and Industry

In the past industry involvement in particle physics detectors has been limited to providing mostly components or very bulky items. Workshops in institutes and at CERN did everything which was complex or costly. In the course of time with detectors becoming more complex, and with assemblies of very large numbers of pieces to be done experiments turned more to industry and often to aerospace industry.

At this time and in Europe universities, particle physics institutes and centres continue to perform detector physics and prototyping for the large LHC experiments as well, of course, as particle physics research.

The spectrum of other activities involved in the development, fabrication and commissioning of large collider detector projects involves possibly two types of industrial concerns: component fabricators and system builders and integrators. Further distinctions concern conventional components and high technological components.

High tech components such as microprocessors, radiation hard electronics, ASICS, any objects requiring complex tooling or production lines or pieces made from metals like tungsten, or from composites, transparent materials are obtained from industry.

In former experiments industry was asked to deliver series products with little integration required. Integration of detectors and their subsystems was organized in regional particle physics centres and at CERN.

The scale and complexity of the LHC detectors require more structured means of technical management and configuration control. A strong emphasis on reliability is also called for. Industrial system builders have a large amount of experience and expertise that is clearly applicable, especially in the fields of series production of complex items.

The details of the coming relation between LHC experiments and industry is not clear yet. The driving consideration, however, will be the efficient and least costly use of the limited resources charged to the experiment in question. Particle Physics can learn from industry to structure and monitor the work properly. Engineering Data Management, to be mentioned below, is such an application of industrial practice.

The closest approach to an "industrial" relation by now is the design and industrial follow-up of the large super conducting magnets to be performed by national laboratories having specialised engineering teams in this field. The cost of these activities is partially or completely charged to the collaborations in a manner approaching industrial circumstances. Basis of the discussion is the full cost recovery of the engineering and R&D efforts by the institute charged with the realisation of such magnets.

The negotiations concerning such activities show the value of the structured means of technical management to control the cost of the activity in the view of obtaining the best results. These means will also benefit construction in industry and equally in institutes or group of institutes. The precise sharing between industry and institutes will depend on local circumstances of manpower cost charged to the experiment, availability of qualified industry and their cost and the complexity of the task in question.

Engineering means of industry are normally simpler than those of the physics institutes. 2-D CAD based on PC are the standard means. Transfer of data takes often place by sending floppies or printed drawings instead of using the network.

Most probably in most cases and especially for complex equipment project leadership will remain with the experimental teams and not be delegated to industry.

6 The ATLAS Detector, its Organisation and Engineering Requirements as one example of CERN LHC Experiments

The ATLAS experiment is described in its physics goals, technical details and collaboration composition in its Technical Proposal (CERN/LHCC/94-43; LHCC/P2; 15 December 1994) The collaboration consists at this time (July 1996) of 1606 participating physicists from 148 institutes from more than 30 countries.

The detector will occupy a cylindrical space of 24m diameter and 50m length. Its weight will be around 6000 metric tons. The detector will have more than 10^8 individual detection channels arranged in more than 20 major sub-systems. Each subsystem will be put together by many widely dispersed institutes chosen for their willingness and capability to undertake work on a given subsystem. The detector will be located in an underground cavern about 100m below the surface opposite to the main entrance of CERN. The cost of the bare detector and accounting only for industrial costs will be 475 MCHF. To this the cost of the cavern and the infrastructure have to be added. The engineering tasks and the resources are therefore highly dispersed and merit to be looked at also under the heading of distributed engineering.

ATLAS ORGANIZATION

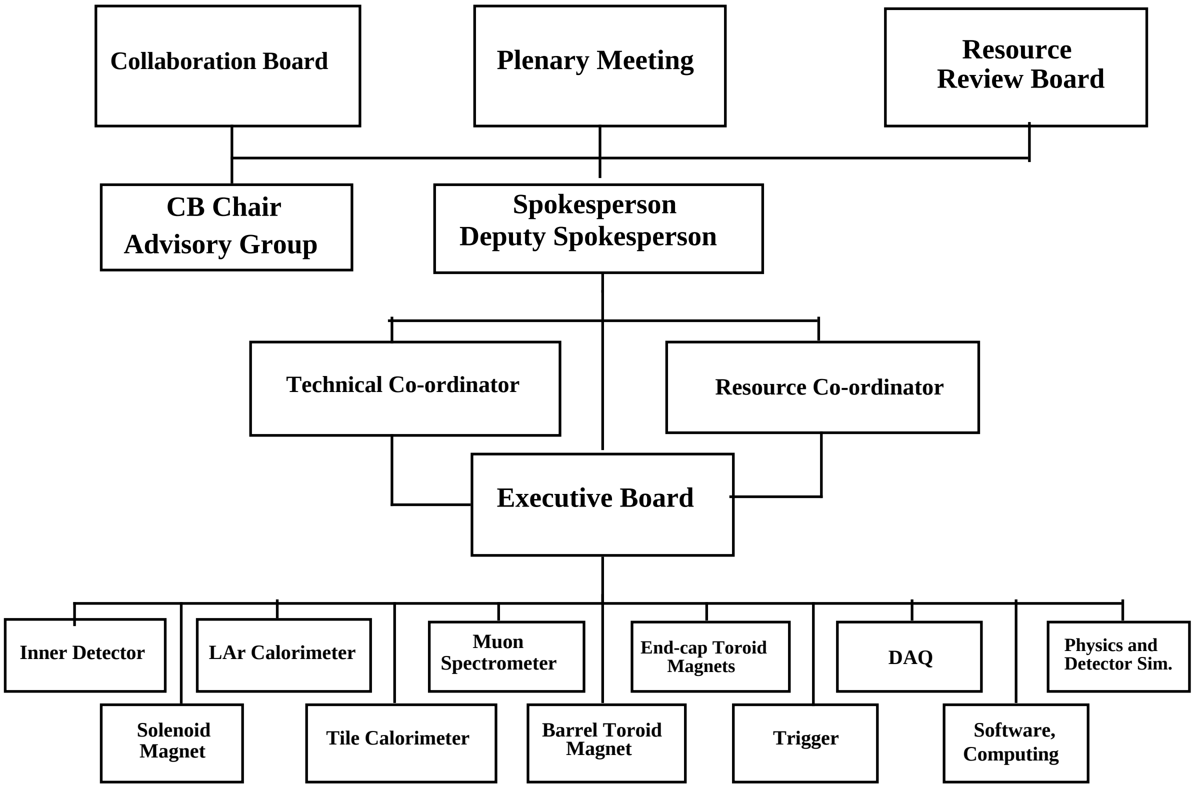

Figure 3: Global Organisation chart of the ATLAS Collaboration

The ATLAS engineering organisation follows the ATLAS organisation, which was adopted in ATLAS in 1994 (ATLAS Technical Proposal, CERN/LHCC/94-43) and is explained in Fig. 3.

The executive part of the organization consists of the Spokesperson with his Deputy, the Technical and Resource Co-ordinators which form the ATLAS management and the Executive Board with representatives of all systems and other important aspects of ATLAS. Operational decisions are taken in the Executive Board, policy or large funding decisions are prepared there and then decided in the Collaboration Board or the Resource Review Board. Mutatis mutandis the decision making process in the ATLAS sub-systems is similar. Decisions affecting only the subsystem are taken there and those affecting more than one system are referred to the technical or resource co-ordination. More important items are referred to the Executive Board or further on.

The underlying principle of the organisational chart is the similar to the widely debated European "Subsidiarity" and in industry probably to the "lean" management. The basic principles are:

- Give a maximum of responsibility to the units doing the work and provide them with precise interface specifications;

- Establish efficient collaborative supervision and reporting concerning performance, resources and integration or interfaces between systems and parts of the detector and its infrastructure.

After the Technical Proposal the tasks of this management have been, and are, to arrive at "Technical Design Reports (TDR's)" by end 1996 and early 1997 for all ATLAS systems. In essence the writing of these reports demands engineering design of all components sufficient to write specifications for industrial procurement of all parts or items to be bought from industry. Assembly and integration knowledge of systems must have been obtained by production of pre-series modules (module Ø). Equally, the integration and resource aspects will have to be treated in detail as well as general scheduling and assembly, operation and maintenance schemes, These reports together will provide for a complete baseline description of the detector.

The engineering organisation follows the general ATLAS organisation. At the Technical Co-ordination level the general engineering framework, the interfaces between systems, the infrastructure, services and common projects are managed. Such a framework has the following ingredients which are listed below in hierarchical layers.(compare Fig. 4)

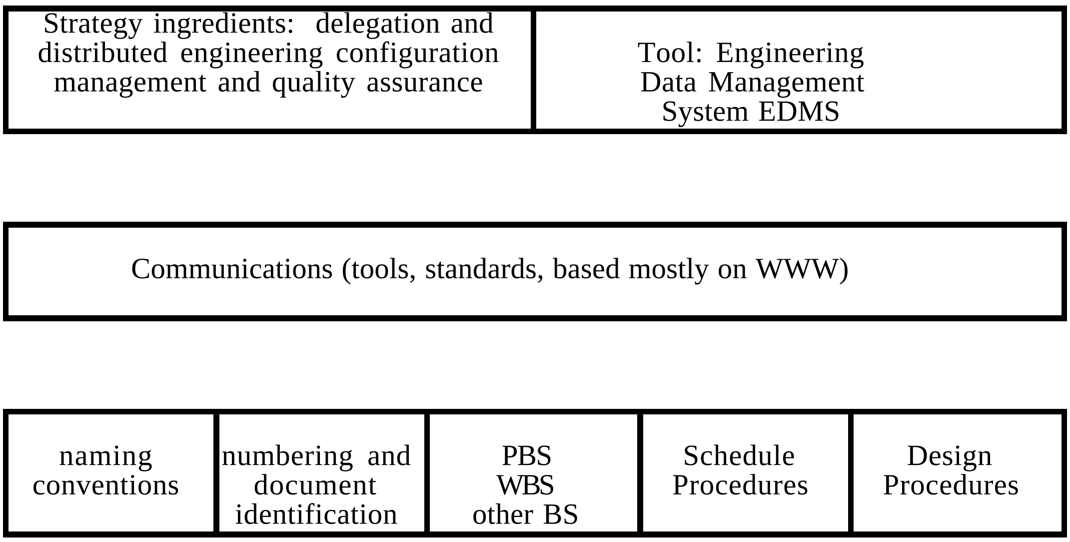

Figure 4: Layers of engineering organisation

The underlying principle of the strategy must be to build the detector in the configuration presently agreed upon by the collaboration.

Today the configuration can be described by the contents of the Technical Proposal and the major changes communicated to the Peer Review Committee and the minor changes agreed in the Executive Board and the even more minor changes agreed upon within the individual systems. The next configuration will be described in the TDR's and later amendments.

The engineering strategy must assure that everybody works on the same agreed detector at all times. The "control procedures" of the strategy must follow the general organization of ATLAS where decisions follow the hierarchy of the organizational chart. Explicitly this means that only matters changing the performance of an item to fall below the agreed specifications and changes of items affecting other detector parts have to be controlled at the level beyond the individual system. Inside the individual systems similar procedures must be established for sub-systems and components.

The engineering strategy therefore also has the aim to assure the "quality" of the detector parts where "quality" stands for conformity with pre-determined performance specifications, envelopes and other parameters.

The tool which will mirror the strategy and is conceived to keep control of the ATLAS configuration is the Engineering Data Management System (EDMS).

The request for this tool originated in ATLAS and found a resonance in the other LHC projects and in the LHC. The original request was motivated by the very long duration of the ATLAS project and therefore by the idea to have a complete set of documentation, description of procedures such as access procedures, technical, operational and repair procedures, details of all parts of ATLAS organized in a hierarchical database available throughout the life cycle of ATLAS, namely about 25 years from conception to termination. The further goal was to include configuration and quality control. One detail of that will be a "subsidiary" approval structure of engineering drawings. The EDMS is described in another contribution to this school.

The other two layers of engineering organization described above then follow naturally, namely, communication means and communication organization. All engineering tasks and efforts are spread out over the entire world ("over ATLAS the sun never sets") and require continuous easy communication between physicist and especially between engineers and their CAD systems. Such communication must be regulated in terms of status and designation of drawings exchanged. In ATLAS the communication engineering communication will be based on the Web. Another talk in this conference concerns engineering communications.

Finally the basis for all orderly behaviour of engineering data are the detailed definitions and conventions for the specialists such as nomenclature, numbering, PBS, WBS, etc.

In ATLAS the top layers and principles of the engineering organisation are being discussed and agreed upon. Descriptions of draft or agreed papers on these subjects are given in the Web pages of ATLAS engineering information (http://atlasinfo.cern.ch/Atlas/TIE/drawing.html) The details keep changing and are continuously updated. They will be more stable later this year. A good introduction into the formalities of the engineering organization is given in Ref. 1.

7 Other Engineering Tools - A List of Requests

Virtual Reality is as of today a showcase of computer performance, good for the public and those not familiar with the details of an experiment. It is limited by the speed of build-up of the images and above all by the detail required to become useful for engineers and people working on integration parts of equipment to a whole. Examples of the assembly of parts of the ATLAS detector are given. They will be reproduced on the ATLAS engineering pages of the Web soon and for the time being as a public relation exercise. The challenge of this will be to create the final detailed envelope of one of the moving parts of the detector with all services attached and then to move this object along its predetermined path with the final detailed environment around and with the planned or calculated deformations of the services attached to the moving parts. The space used must not have a single intersection with fixed components. The minimal distances from the moving parts to the fixed parts are to be determined and plotted to show difficult regions.

Dynamic finite element calculations showing the movements under the build-up of magnetic forces of the large super conducting magnets and the attached detectors would be another interesting item. There may be many more possibilities.

To organize the easy transfer of even detailed geometries between various simulation and calculation programs and 3-D CAD has already been mentioned. This will be a major STEP (ISO mentioned before) towards uniting efforts of physicists and engineers.

The time to develop such programs or the time required to implement the geometries and to do the calculations should be short compared to the capabilities of a good engineer with his pocket calculator and his acquired knowledge of the apparatus he considers. Else the performance and precision of the calculation must be clearly superior and also necessary. Furthermore the available resources must match the ambitions. Here is probably a good field of co-operation of particle physics laboratories, industry and engineering universities or high schools.

Finally, the video-conference/M-bone or other communication means of two engineers or groups of engineers/physicists to discuss ad hoc problems independent of location of their institute and using the same drawing for their discussion is of the highest priority in the coming years.

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