Reducing the Human-in-the-Loop Component of the Scheduling of Large HTC Workloads

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Abstract. A common characteristic to major physics experiments is an ever increasing need of computing resources to process experimental data and generate simulated data. The IN2P3 Computing Center provides its 2,500 users with about 30,000 cores and processes millions of jobs every month. This workload is composed of a vast majority of sequential jobs that corresponds to Monte-Carlo simulations and related analysis made on data produced on the Large Hadron Collider at CERN.
To schedule such a workload under specific constraints, the CC-IN2P3 relied for 20 years on an in-house job and resource management system complemented by an operation team who can directly act on the decisions made by the job scheduler and modify them. This system has been replaced in 2011 but legacy rules of thumb remained. Combined to other rules motivated by production constraints, they may act against the job scheduler optimizations and force the operators to apply more corrective actions than they should.
In this experience report from a production system, we describe the decisions made since the end of 2016 to either transfer some of the actions done by operators to the job scheduler or make these actions unnecessary. The physical partitioning of resources in distinct pools has been replaced by a logical partionning that leverages scheduling queues. Then some historical constraints, such as quotas, have been relaxed. For instance, the number of concurrent jobs from a given user group allowed to access a specific resource, e.g., a storage subsystem, has been progressively increased. Finally, the computation of the fair-share by the job scheduler has been modified to be less detrimental to small groups whose jobs have a low priority. The preliminary but promising results coming from these modifications constitute the beginning of a long-term activity to change the operation procedures applied to the computing infrastructure of the IN2P3 Computing Center.

1 Introduction

In the field of high-energy and astroparticle physics, detectors, satellites, telescopes, and numerical simulations of physical processes produce massive amounts of data. The comparison of these experimental and simulated data allows physicists to validate or disprove theories and led to major scientific discoveries over the last decade. For instance, in 2012, the ATLAS [10] and CMS [11] experiments running on the Large Hadron Collider (LHC) at CERN, both observed a

new particle which is consistent with the Higgs boson predicted by the Standard Model. These observations confirmed a theory of the origin of mass of subatomic particles which was awarded the Nobel Prize in physics in 2013. In 2016, the LIGO and VIRGO scientific collaborations announced the first observation of gravitational waves [13] which confirmed the last remaining unproven prediction of general relativity.

The next decade will see the beginning of major projects that will allow astroparticle physicists to address the most pressing questions about the structure and evolution of the universe and the objects in it. From 2022, the Large Synoptic Survey Telescope (LSST) will conduct a 10-year survey of the sky to produce the largest catalog of celestial objects ever built while the Euclid spatial telescope aims at drawing a 3D map of hundreds of millions galaxies from 2020.

A common characteristic to all these physics experiments is an ever increasing need of computing and storage resources to process and store experimental data and generate simulated data. Moreover, the sheer amount of data produced by physics experiments enforces the distribution of data and computations across a worldwide federation of computing centers.

The Computing Center of the National Institute of Nuclear Physics and Particle Physics (CC-IN2P3) [12] is one of the largest academic computing centers in France. It provides its more than 2,500 users from 80 scientific collaborations with about 30,000 cores and 340PB of storage. The reliability and high availability of the CC-IN2P3 allows it to achieve an utilization of these resources above 90%. In particular, the CC-IN2P3 is one of the twelve Tier-1 centers in the Worldwide LHC Computing Grid (WLCG) engaged in the primary processing of the data produced by the LHC and one of the only four centers that provide storage and processing resources for all four experiments installed on the accelerator.

This participation in the WLCG strongly influences the organization and the operation of the computing at the CC-IN2P3. It also defines and shapes the workload that is executed. Indeed, the four LHC experiments alone have used up to 75% of the allocated resources. In 2017, they represented 56% of the allocations, as the needs expressed by other experiments have been increasing.

The main characteristic of the CC-IN2P3's workload is that it is a High Throughput Computing (HTC) workload composed of a vast majority of sequential jobs. It mainly corresponds to Monte-Carlo simulation jobs and related data analysis made on the data produced at the LHC. We observed an increasing share of multi-core jobs (i.e., using several cores within the limits of a single node) in the workload over the last three years. Some of these multi-core jobs are really exploiting the computing capacities of all the cores they request, but they may also allow physicists to access a larger memory space. Finally, HPC jobs (e.g., using MPI or GPUs) are executed on a distinct set of nodes, which only represents a small fraction of the overall computing capacity of the CC-IN2P3.

The requirements of the main experiments running at the CC-IN2P3 influence the performance metrics the job scheduling system has to optimize. Indeed, the resource allocation procedure differs from that of traditional HPC centers

where scientific collaborations usually submit a research proposal which includes a request for an *envelope of cores.hours* to use during a limited time period. For a Tier-1 center of the WLCG such as the CC-IN2P3, resource requests are expressed as pledges for a given *computing power* expressed in HS06 [9]. The computing center is then committed to provide enough resources to answer to those pledges. Moreover, the accounting is made with regard to the actual CPU usage of a job rather than on its duration. This allocation procedure has been extended beyond the four LHC experiments to all the groups computing at the CC-IN2P3. The main objectives for the batch scheduling system are thus to ensure a fair sharing [4] of the resources according to the different pledges and to guarantee that all the pledges are respected. These objectives are translated into priorities and quotas assigned to jobs and user groups.

Scheduling also has to take into account the data-driven nature of the executed jobs. Several experiments running at CC-IN2P3 make a heavy use of the different storage subsystems the center provides (e.g., GPFS, HPSS, iRODS). To prevent the saturation of a storage subsystem and a failure which could have a cascading impact on the execution of the workload, additional conservative quotas are assigned to groups to limit the number of concurrent running jobs.

To schedule such a peculiar workload with regard to the aforementioned constraints and objectives, the CC-IN2P3 developed and maintained its own in-house job and resource management system for nearly 20 years. The development of the *Batch Queuing System* (BQS) started in 1992 and was initially based on NASA's *Network Queuing System* (NQS). This system has been tailored to suit the specific needs of the computing center and its major users. For instance, it was possible to "program" the scheduler to meet the production objectives expressed by the different experiments. Moreover, the respect of a fair sharing of the resources among the scientific groups and accounting mechanisms to ensure the respect of the pledges were part of the initial design.

The job and resource management system is complemented by a team dedicated to the operation of the computing infrastructure that adds an important "human-in-the-loop" component to the scheduling of the workload. Indeed, the role of the operators is not limited to reacting to incidents related to either resources or jobs. They can also directly act on the decisions made by the job scheduler and modify them. For instance, an operator can manually boost or lower the priority of a job/user/group or change the allocations of resources to a given queue in a proactive way.

The decision to stop the development of BQS was taken in 2011. It had become too costly in terms of human resources over the years. Since then, the job and resource management system of the CC-IN2P3 is Univa Grid Engine [14]. However, some legacy rules of thumb from the operation of BQS remained and add to the different rules motivated by the constraints on the hardware and software resources and the respect of pledges. This accumulation of rules sometimes acts against the job scheduler optimizations and forces the operators to apply more corrective actions than they should.

In this experience report from a production system, we describe the decisions made since the end of 2016 to transfer some the actions done by operators to the job scheduling system or simply make these actions unnecessary. The objective is to improve the job scheduling decisions, especially for small user groups and optimize the resource utilization, while minimizing the "human-in-the-loop" component in such decisions Three complementary modifications have already been implemented which deal with: (i) the partitioning of resources; (ii) the quotas assigned to the different user groups; and (iii) the computation of the fair-sharing by the job scheduler.

The remaining of this paper is organized as follows. First, we describe how large HTC workloads are processed at the CC-IN2P3 in Sect. 2 by detailing its computing infrastructure and scheduling and resource allocation procedures and characterizing the executed workload. Then, in Sect. 3, we motivate, present, and illustrate the benefits, be they an optimization of the scheduling and/or a reduction of the operation costs, for each of the three proposed modifications. Section 4 concludes this experience report and details future work directions.

2 Scheduling Large HTC Workloads at CC-IN2P3

2.1 Organization and Management of the Computing Infrastructure

As mentioned in the introduction, the CC-IN2P3 provides its users with about 30,000 *virtual* cores (i.e., hyper-threading is activated on physical cores). More precisely, and at the time of writing of this article, this computing infrastructure is made of 723 nodes whose characteristics are given in Table 1. Due to the ongoing upgrade of the default Operating System from Scientific Linux 6 to CentOS 7, this set of nodes is currently seen by the job and resource management system as two distinct partitions of respectively 626 and 97 nodes. This allows the user groups to prepare the migration of their codes at their own pace. Nodes are progressively moved from one partition to the other, this migration being scheduled to be complete by June 2018.

In addition to these nodes that are dedicated to the execution of the HTC workload, the CC-IN2P3 also offers resources for parallel (512 cores without hyper-threading in 16 nodes) and GPU-based (32 NVIDIA K80 GPUs and 128 cores in 8 nodes) jobs, and five nodes dedicated to interactive jobs.

Table 1: Characteristics of the nodes in the CC-IN2P3's computing farm.

Model	**#Nodes**	**#vCores / Node**	**#vCores**
Intel Xeon E5-2650 v4 @ 2.20GHz	232	48	11,136
Intel Xeon E5-2680 v3 @ 2.50GHz	124	48	5,952
Intel Xeon E5-2680 v2 @ 2.80GHz	147	40	5,880
Intel Xeon E5-2670 0 @ 2.60GHz	220	32	7,040
Total	**723**		**30,008**

These computing resources are managed by Univa Grid Engine (UGE v8.4.4). The scheduling algorithm of UGE is an implementation of the *Fair Share Scheduler* first described in [5]. Its principle is to assign priorities to all the unscheduled jobs to determine their order of execution. These priorities derive from three fundamental policies. The first policy is related to the *entitlement* of a job to access resources. It relies on the implementation of the *Share Tree* policy which defines this entitlement of a job according to the previous resource usage of a user/project/group. The administrators of the systems first define a total number of *tickets* which basically corresponds to a virtualized view of the complete set of resources managed by the system. This total number of tickets is then distributed among groups (and then among sub-projects, users, and eventually jobs). In the configuration used at CC-IN2P3, the different shares are proportional to the resource pledges expressed by the different user groups. When a given group A does not use its allocated share, pending jobs of other groups are allowed to use these resources. The group with the least accumulated past usage has the highest priority in that case. However, when group A starts to submit jobs again, a compensation mechanism is triggered to allow this group to reach back its targeted share. Figure 1 illustrates the behavior of this policy.

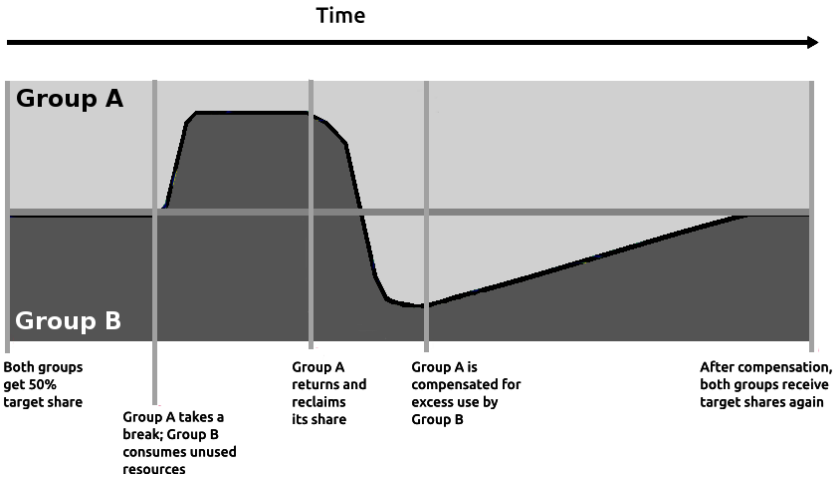


Fig. 1: Example of the Share-tree policy applied to two user groups allowed to use a half of the resources each.

Two parameters control this mechanism. The *half-life* specifies how UGE forgets about the past usage of a given group. This parameter thus acts on the selection of groups allowed to benefit of the resources left unused by another group. The second parameter is the *compensation factor* that limits how fast a group will reach back its targeted share. The higher the value, the more reactive to variations in the workload the system will be. The current values used at CC-IN2P3 are 2,160 for the half-life and 2 for the compensation factor.

The second policy implemented by UGE corresponds to the expression of the urgency of a job and defines some weights in the computation of the priority of the job. This urgency is decomposed in three components. First, the closer job is to its deadline (if one has been specified at submission time, which is not the case at CC-IN2P3), the higher its priority will be. Second, the priority will also increase along with the waiting time of the job in the scheduling queue. Finally, a higher priority will be given to jobs that request expensive resources. For instance, at CC-IN2P3, resources are organized in queues whose characteristics are given in Table 2. These queues mainly differs by the maximum duration, both in terms of wallclock and CPU times, of the jobs, the available virtual memory and scratch disk space, and the type of jobs, i.e., sequential or multi-core. In the current configuration, a higher weight is given to the multi-core queues, which are thus more "expensive" than sequential queues.

Table 2: Characteristics of the batch scheduling queues.

Queue	**Max. CPU time (hh:mm:ss)**	**Max. walltime (hh:mm:ss)**	**Max. memory (in GB)**	**Max. disk space (in GB)**	**Max. #vCores**
huge	72:00:00	86:00:00	32	110	4,678
long	48:00:00	58:00:00	16	30	15,053
longlasting	168:00:00	192:00:00	16	30	1,818
mc_huge	72:00:00	86:00:00	32	30	8,600
mc_long	48:00:00	58:00:00	16	30	29,902
mc_longlasting	202:00:00	226:00:00	16	30	18,896

The sum of the maximum numbers of virtual cores that each queue can use is more than 2.5 times the actual number of available cores. This guarantees the highest possible utilization of the resources but also prevents the saturation of queues. Any type of jobs thus has a good chance to access resources, hence increasing the quality of service experienced by the users, who are not advised to specify a queue on submission. They are encouraged to express job requirements instead and let the scheduling system select the most appropriate queue.

The configuration of these queues also illustrates the operational priorities of the CC-IN2P3. We can see that the `mc_*` queues dedicated to multi-core jobs are allowed to access much more cores than the queues reserved to sequential jobs. This confirms the higher priority given to multi-core jobs which now represent the majority of the CPU consumption as the characterization of the workload given in Sect. 2.3 will show. We also note that jobs are not really distinguished by their execution time in this configuration. Indeed, the `huge` and `mc_huge` queues are primarily intended to jobs that need more memory or disk space. Moreover, the access to the `longlasting` queues is limited to certain user groups. Then, most of the workload is directed to the `long` and `mc_long` queues. The rationale

is to simplify the computation of the fair-sharing by the job scheduler whose respect is the main operational objective. However, this also means that all jobs are scheduled taking the upper bound of the queue as walltime. Indeed, users are not advised to specify any estimated duration when they submit a job. This lack of information can have two drawbacks. First, it may be harmful to the scheduler as it has to cope with important discrepancies between the "estimated" and actual duration of the jobs, as we will see in Sect. 2.3. Second, short jobs submitted by small groups whose priority is low with regard to the global fair sharing policy may be severely delayed. Indeed, their short duration is not translated in an increase of their priority.

The last component in the computation of job priorities by UGE is the capacity for users to manually specify a POSIX priority at submission which only acts as another weighting factor in the formula used to determine the overall scheduling priority of the job.

In addition to these policies implemented by the job and resource management system, a last configuration parameter has a strong influence on scheduling. This is the definition of limitations as *Resource Quota Sets* (RQS). These limitations are expressed as a maximal number of virtual cores (or slots in the UGE terminology) that can access a given hardware of software resource and thus be allowed to enter the system. They are applied at two levels. Global limitations are applied to all groups and jobs indifferently. Such limits are classically used to define resource pools (e.g., depending on the operating system running), prevent the saturation of a storage or database service, or are related to the number of available license tokens for commercial software.

In the specific configuration of the CC-IN2P3 system, extra RQS are applied to groups to either limit the number of concurrent jobs or the number of jobs accessing a given resource. The former is used as a way to enforce the respect of the resource pledges expressed by each group by averaging their estimated consumption over the whole year. The latter corresponds to the implementation of a conservative approach to further prevent the saturation of sensitive storage subsystems such as a shared parallel file system.

2.2 Resource Allocation Procedure

Every year in September, the representative of each of the scientific collaborations using the CC-IN2P3 is asked to pledge resources for the next year. Each group provides an estimation of its needs in terms of computing and storage on each of the available subsystems. While the large collaborations such as those of the LHC experiments have a well defined and planned definition of their requirements at a worldwide scale, smaller groups usually define their needs from their consumption of the previous year with an empirically estimated delta.

The accuracy of these pledges is critical for two reasons. First, the sum of the expressed requirements, combined to the available budget, define, after an arbitration process, the purchase of new hardware to ensure that the CC-IN2P3 can fulfill its primary mission and serve all the experiments. This is another major difference with traditional HPC centers that buy and host the biggest

affordable supercomputer and then arbitrate the demands with regard to the capacity of this machine. Second, the pledges define the Resource Quota Sets applied to each group and thus have a direct impact on job scheduling.

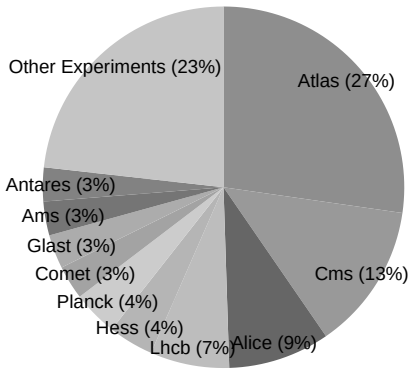
The allocation of computing resources works as follows. Each group expresses its pledge as an amount of work to be done during the year. This amount is given in *Normalized HS06.hours*, a unit coming from the High Energy Physics community. It corresponds to the normalization of the results of the HS06 benchmark [9] on the different types of nodes in the computing infrastructure to take node heterogeneity into account multiplied by a number of hours.

The accumulation of all the required numbers of HS06.hours defines the computing power the CC-IN2P3 has to deliver. Once arbitration has been done, the respective share of this total number that has to be allocated to each group is computed. Then this share is converted into a number of virtual cores needed to process this amount of work in a year. Finally, this number of virtual cores defines a consumption objective used by the job scheduler to compute its fair-sharing.

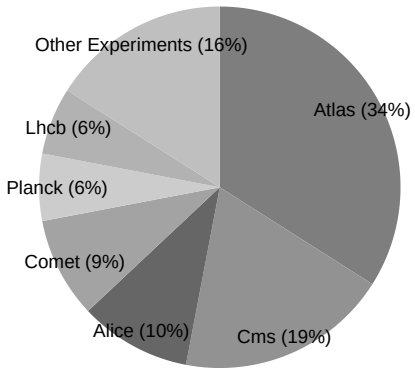
Figure 2a shows how the pledges for computing power were distributed among the different user groups in 2017. This graph only distinguishes the top ten requests. The "Other Experiments" section aggregates the pledges of the 70 other user groups and amounts for 23% of the sum of the pledges. We can also see that the four LHC experiments (ATLAS, CMS, Alice, and LHCb) represent 56% of the demands. The remaining 21% are almost evenly distributed among six user groups. This distribution explains why the whole allocation procedure and the performance objectives assigned to the job scheduler are driven by the demands of the LHC experiments.

Fig. 2: Distribution of the computing resource requests (a) and consumptions (b) among the different scientific collaborations using the CC-IN2P3.

(a) Pledges for 2017



(b) Usage in November 2017



2.3 Characterization of the Workload

We analyzed the workload processed at CC-IN2P3 over a month in November 2017. We extracted and combined information on jobs from two tables (i.e., `view_accounting` and `sge_job_usage`) of the Accounting and Reporting Console (ARCo) provided by Grid Engine to obtain something similar to the Standard Workload Format (SWF) [1]. This log is composed of 2,135,755 individual jobs. More than 85% of these jobs (i.e., 1,823,789 jobs) are sequential, while the vast majority of the remaining 15% of the workload is made of 8-core jobs. However, if we consider the cumulative run time of these two types of jobs, we observe a different distribution. The multi-core jobs represent about 53% of the residency time on the computing platform. More precisely, 94% of these multi-core jobs are submitted by only two users groups: ATLAS (72%) and CMS (22%).

We start this analysis by comparing the CPU usage made by the different user groups to the expressed pledges. This is a way to measure how well the job scheduler allocates resources to groups with the objective of respecting a fair sharing that derives from the pledges. Figure 2b shows the observed distribution, which confirms the respect of the fair sharing of resources. We only distinguish the groups that represent more than 3% of the CPU consumption in this graph. Except for HESS, all the experiments with the largest pledges were also the largest users in November 2017.

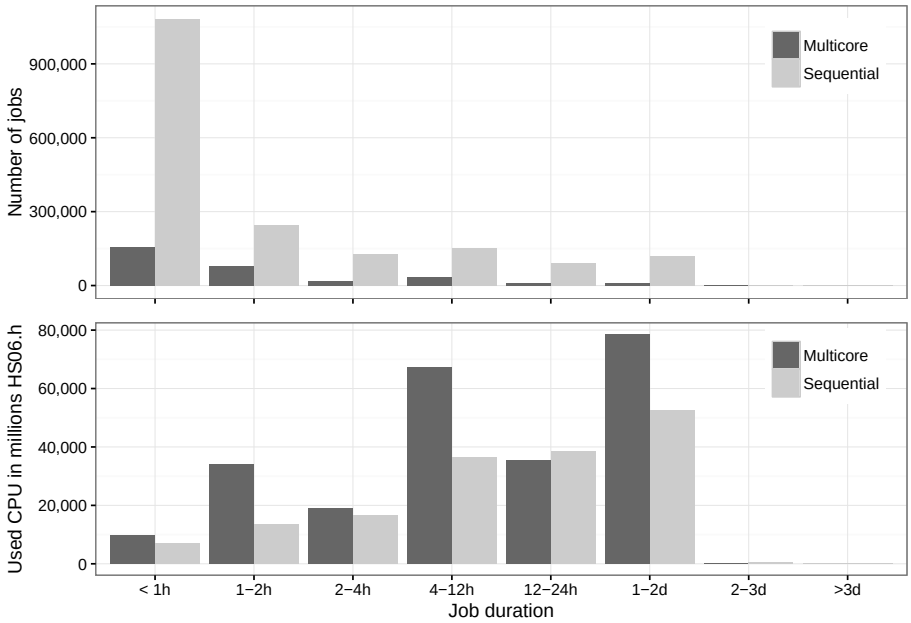
In this preliminary characterization of the workload, we only considered a month of workload, which already represents a large number of jobs to analyze. This prevented us to study how the submission patterns of the different groups vary over the year in periods of high or low activity. However, such patterns are known and captured by other monitoring tools used by the operation team. Observing the workload over only a short period leads to the differences between the yearly objective and the measured resource usage shown in Fig. 2.

The definition of scheduling queues and the limits they enforce usually reflects the characteristics of the workload. For instance, a classical rule is to assign to a queue a number of resources that is inversely proportional to the duration of the jobs submitted in this queue [7]. The rationale is that the system can afford to concurrently execute a large number of short jobs, as they will release the resources soon. Conversely, the number of long running jobs has to be controlled to prevent large delays for shorter jobs caused by the lack of available resources.

We saw in the previous section that the job and resource management system of the CC-IN2P3 does not define queues according to the duration of jobs. In the studied log, 74.4% of the submitted jobs are in the `long` or `mc_long` queues whose limits are set to two days of CPU time. 7.2% are "long lasting" jobs that can consume for up to 7 days of CPU time, while the remaining 18.4% correspond to "huge" jobs which are limited to three days of CPU time. However, if we look at the distribution of job duration shown by Fig. 3 (top), we see that this configuration might not be optimal.

First, we can see that less than 1,250 jobs have a duration greater than two days, which is the limit between the `long` and `longlasting` queues. More precisely the vast majority of the jobs submitted to the two `longlasting` queues

Fig. 3: Distribution of the number of jobs (top) and corresponding CPU usage (bottom) according to their actual duration in November 2017.



last for less than a day. This indicates that groups with an access to this reserved queue submitted jobs that should have gone in the regular `long` queue.

At the other end of the range of job duration, we see that 58% of the studied workload is composed of jobs that run for less than an hour. In fact 48% of these short jobs are completed in less than 10 minutes. This corresponds to two situations. Some groups submit pilot jobs that start but stop as soon as they realize they have nothing to do. Other jobs may not succeed to access to the storage and end without being considered as failed by the job scheduler.

Figure 3 (bottom) shows that the majority of the system utilization comes from jobs that runs from 4 to 48 hours, while they only represent a small fraction of the total number of jobs. This also confirms the impact of multi-core jobs on the CPU consumption which only account for 15% of the submissions but more than 50% of the utilization.

This analysis pleads for a redefinition of the scheduling queues, and the pools of resources they can access to take the characteristics of the workload into account. The importance of the configuration of the queues on the quality of the produced schedules has been outlined in [7,6]. Such a work still has to be done at CC-IN2P3 and will require to measure and balance the effects of adding more queues to the system with regard to the respect of the fair-sharing of the resources, hence the respect of the pledges made by the user groups.

3 Reducing the Human-in-the-Loop Component

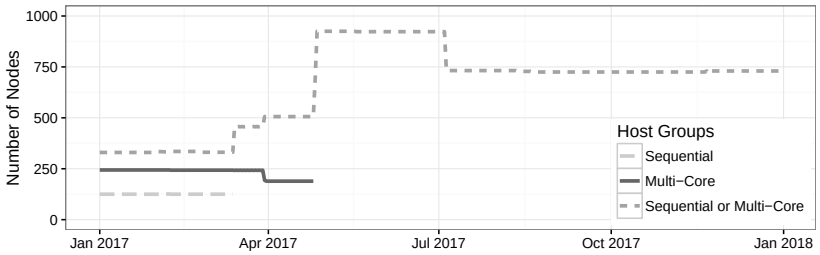
In this section, we motivate and explain the modifications made to the configuration of the job and resource management system over the last year. However, this experience report does not include any quantification of the benefits of these modifications. The main objective was to reduce the burden put on operators by improving the decisions made by batch scheduling system, hence automating some of their daily interventions. Such interventions were not tracked before the modifications. The evaluation of the gain would thus have been subjective and difficult to quantify.

3.1 From Physical to Logical Resource Partitioning

Despite the efforts made while purchasing new hardware to keep the computing infrastructure as homogeneous as possible, nodes used to differ a lot in terms of CPU power and amount of memory from one model to another. A direct consequence of this heterogeneity was that some nodes were more suited than others to the execution of the 8-core jobs that require more memory. As mentioned in the previous section, almost all of these jobs are submitted by the two main experiments (in terms of resource allocation and consumption) running at the CC-IN2P3. They are thus considered of the highest priority.

Before March 2017, the computing infrastructure was physically partitioned in three *host groups* as shown in Fig. 4. One was dedicated to sequential jobs (125 nodes), another to multi-core jobs (245 nodes), and the third and largest one (330 nodes) accepted the execution of both sequential and multi-core jobs.

Fig. 4: Transition from a physical to a logical node partitioning in 2017. The variation of the number of nodes from May to July corresponds to the period between the reception of new nodes and the decommission of old hardware.



The primary motivation of such a partitioning was to guarantee that the high priority multi-core jobs can start without having to wait for the completion of several sequential jobs. A secondary motivation was to keep the capacity to allow sequential jobs to run on these nodes dedicated to multi-core jobs when they become idle. The major physics collaborations such as ATLAS or CMS usually

execute an important part of their computations during planned *campaigns*. They are also able to coordinate the use of multiple computing centers at a continental scale to distribute the load. Then, there can be important variations in the job submission pattern, and period of low load could be exploited by other user groups. However, the management of distinct resource pools also had a high operational cost. For instance, if a decrease in the submission of multi-core jobs by the ATLAS experiment was detected by the operators, they first had to check with the dedicated support to determine if this behavior was expected and know the duration of the lower load period. Then nodes were manually reassigned to the mutualized host group to keep them utilized. A safety margin was kept in case the submission rate of ATLAS starts to increase earlier than excepted. This safety margin could be exploited by other groups running multi-core jobs such as CMS, but as the estimated end of the low load period got closer, more stringent limitations had to be manually applied to these groups.

With the end of Moore's Law, the node heterogeneity tends to disappear. New processors have more cores but there are no important clock rate deltas from one generation to another anymore. The historical physical partitioning of the resources is thus no longer justified. To simplify the management of the computing infrastructure, it has been replaced by a logical partitioning. In other words, the existing host groups have been merged, as shown by Fig. 4, and the distinction between sequential and multi-core jobs is now handled by the queues presented in Table 2. This change is almost transparent for the users (who are not supposed to specify a queue) as the job scheduler can automatically assign multi-core jobs to one of the `mc_*` queues. However, this is an important change from the operational point of view. Indeed, operators no longer have to manually specify the boundaries of the resource pools based on experience and rough estimations of the foreseen evolution of the submission patterns. This burden is now transferred to the job scheduling system which has been designed to adapt its decisions according to the respective filling of the queues.

3.2 Simplification of the Access Rule and Quota Mechanisms

The origin of the definition of *resources* and the application of quotas on these resources goes back to the use of the BQS job and resource management system. The term "resource" first encompassed job related parameters such as the required operating system, the needed amount of memory, the maximum CPU time, or the queue in which to place the job. This definition was rapidly extended to cover the different services offered by the CC-IN2P3 that a job could need.

A motivating example for such a definition of resources and quotas is the case of a job that need to fetch data from a distributed storage system S_1, store the produced results on another storage system S_2, and also needs to access a relational database D during its execution. Such a job can succeed if and only if all of the three dependencies on external services S_1, S_2, and D can be satisfied. Specifying the needed resources at submission time allows the job scheduler to delay a job if one or more services are not available (e.g., because of an incident or a temporary saturation) to prevent an unavoidable failure of the job.

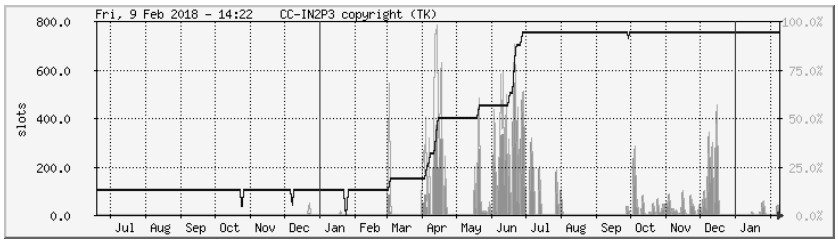
This mechanism has then evolved into a two-level quota mechanism. The first level defines global limits on the number of concurrent jobs that can access a given resources without regard to the submitter. Such limits allow to prevent the different storage subsystems or database services to be overloaded, ensure that the number of license tokens for a commercial software is not exceeded, or define physical pools with different versions of the operating system when an upgrade in underway. The second level specifies quotas for {resource, group} couples. The rationale was to be able to block or limit the access of a given group to specific service more easily. For instance, if a group has filled its allocated disk space on a storage subsystem, jobs that could write more data will be rejected until more space has been granted or cleaning has been made. This also allows operators to easily drain the use of a resource for maintenance operations or incident recovery by blocking all the jobs that expressed a dependency on that resource.

Over the years, this appealing way to ensure a fine regulation of the job submission and to optimize the utilization of the computing and storage infrastructures became a very complex set of rules, thresholds, and locks to control the maximum number of jobs per user, group, machine, or service. The multiplication of resource definitions, hence the accumulation of limits for a given user group not only slows down the scheduling rounds as the job scheduler has to check everything, but also makes it sometimes difficult to understand why some jobs cannot enter the system. For instance, a restrictive limit may have been applied at some point, and for a good reason, to a certain {resource, group} couple and not been reconsidered afterwards. Then, sometimes months later, users complain that their jobs do not run for what they consider as no good reason, because of this persisting but forgotten limit.

At the end of 2016 the decision has been made to simplify the access rule and quota mechanisms. The main objective is to reduce the number of declared *resources* to only keep a minimal set of essential requirements that jobs have to express. The CC-IN2P3 being a production center, such changes have to be done carefully to prevent any major disruption of the activity. The chosen solution was to progressively relax the quota associated to a {resource, group} when it becomes a bottleneck while ensuring that the associated resource can cope with the increase. Figure 5 illustrates this action. Eventually, when the limit is high enough, it obviously becomes meaningless and can thus be safely removed. This was especially done for quotas related to the storage subsystem.

A similar method has been applied to the maximum number of jobs of a group that can run simultaneously. Such RQS were defined as a way to enforce the fair sharing and to be able to rapidly react to an unwanted overconsumption of the resources by a given group. However, this kind of limit was especially harmful to small user groups whose computing needs correspond to short bursts of a large number of jobs every once in a while, for instance just before a deadline for the submission of an article. In such a case, users had to open an issue on the user support ticketing system to explain that they would like to see more of their jobs running. Then, the operation team would grant this exception by manually relaxing the quota and/or boosting the priority of jobs.

Fig. 5: Relaxation of a per-group RQS on a storage subsystem. The black line indicates the maximum number of *slots* (i.e., virtual cores) currently available to the group. The grey part corresponds to the number of used slots.



After a few months of operation, we can conclude that letting the job scheduler deal with submission bursts without any human intervention is a success. The concerned groups reduced their time to solution without harming other groups. This also reduces the load of both the operation and support teams who have less tickets to handle. However, some limits have to be kept for certain groups whose jobs have a specific greedy behavior or are highly sensitive to the accessibility of the storage subsystems.

3.3 Extending the Fair-Sharing History Window

The last important modification made to the configuration of the job scheduler is related to the implementation of the fair-sharing of resources. The basic principle of a fair-sharing allocation is, for each user/group, to assign a priority to jobs that is inversely proportional to the usage of the resources by this user/group over a sliding time frame. The rationale is very simple: if a group already computed a lot, it has to make room for another that did not. Then, this group will compute less (and see its priority increase) while the other computes more (and its priority decreases). A key configuration parameter of such an algorithm is the size of the time frame over which to compute the resource usage.

Until the end of 2016, the size of this history window was set to 24 hours. As for many other parameters, this value was motivated by the predominance of the LHC-related jobs in the workload and the commitment to fulfill the pledges for these experiments made by the CC-IN2P3. Such a short time window was one of the levers to ensure a good reactivity of the system when the largest groups, i.e., ATLAS or CMS, started to submit jobs after a period of inactivity. These jobs got the highest possible priority and were scheduled immediately.

The main drawback of this strategy is that the jobs submitted by groups with much lower priorities suffered from large delays. From the point of view of the users belonging to these groups, the fair-sharing was felt as particularly unfair. To circumvent this issue, the operation team developed several mechanisms to ensure that smaller groups were not disadvantaged. For instance, they develop a script that ensured a minimal number of running jobs per user by modifying the priorities of some jobs to force the system to schedule them earlier. Another

technique was to specify additional resource definitions (as explained in the previous section) dedicated to these groups. Adding a requirement on this "special" resource upon submission allowed the jobs to bypass the fair-sharing mechanism completely and start almost immediately.

The proposed solution to ensure a fair-sharing of the resources for *all* the user groups, be they small or big consumers, without having to bypass or modify the decisions made by the job scheduler was to increase the time frame used to determine the priorities. To prevent any harmful disruption of the production due to this change, we decided to progressively and empirically increase this value. It was first set to 15 days in January 2017, then to 30 days in March, and finally to 90 days in June 2017. After each modification, the operation team monitored its impact on the production. While benefits for small groups and no loss of the quality of service for the largest groups were observed, the time frame was increased. A more principled process based on the particular setting of the CC-IN2P3 would obviously have to be found. However, this would require a parametric study combined to a thorough evaluation through simulations of the impact before being deployed in production that is part of our future work.

The second modification made to the priority determination mechanism is related to the metric used to measure the resource utilization. Historically, the priorities were based on the *used CPU time* because the pledges made by the experiments are expressed as a CPU consumption. This metric is thus used to determine if the computing infrastructure can satisfy all the pledges and for the accounting of the resource usage. However, it may also favor inefficient jobs, i.e., jobs that are unable to fully exploit the CPU. Let's consider two groups that submit one job of the same duration each, one using 100% of the CPU capacity and the other only 50%. Because of the chosen metric, the latter is seen as consuming less resources than the former over the same time period and will end up with a higher priority. Then the subsequent inefficient jobs from the second group will be scheduled earlier even though they "waste" CPU time.

The historical way to address this issue was to add a new quota to limit the number of inefficient jobs running, hence adding more complexity to the scheduling. A simpler solution, adopted in September 2017, is to change the metric from *used CPU time* to *actual execution time*. This simple modification solves the issue of inefficient jobs without adding an extra complexity to the system. For the other jobs the change is transparent.

4 Conclusion and Future Work

The IN2P3 Computing Center is the largest French academic High Throughput Computing center. Its primary mission is to answer the computing and storage needs of the major international scientific collaborations in the domains of high-energy and astroparticle physics. To manage the execution of millions of individual jobs every month on 30,000 cores, the CC-IN2P3 relied for years on an in-house job and resource management system and a complex set of admission rules and quotas on hardware and software resources. However, the ever increas-

ing sizes of both the infrastructure and workload made the existing system too cumbersome and put an heavy load on the operation team.

In this experience report, we presented the specificity of the CC-IN2P3, the large HTC workload executed on its resources, and how complex its operation has become. Then we detailed the work engaged at the end of 2016 to transfer some of the actions done by operators to the job scheduling system with the objective to minimize the "human-in-the-loop" component in scheduling decisions. The proposed modifications that were recently implemented shows preliminary but promising results. However, the work presented in this paper is only the beginning of a long-term activity to change the operation procedures applied to the computing infrastructure of the CC-IN2P3.

Our future work thus includes several directions that we plan to follow. First, we will perform a deeper analysis of the workload to further characterize the jobs and identify leads for improvement. One of the main objective will be to work on a better estimation of the execution time of the jobs. Ideally, we would like to encourage users to provide an estimation of the walltime at submission time as it is classically done on HPC systems. This should both help the job and resource management system to schedule jobs and the operation team to refine the definition of queues. Second, we plan to resort to simulation to assess the impact of potential modifications of the configurations of queues and quotas as proposed in [7,6]. Several tools are available to perform such a simulation study, like Alea [8] or Batsim [2]. The main obstacle is that the "Human-in-the-loop" component that we started to reduce makes it difficult to use logs obtained from the job scheduler and replay them under a different configuration. Indeed, the scheduling decisions taken solely by the job and resource management system may have been tampered by operators, without being reflected in the logs. This may lead to interpretation biases. Further reducing these human interventions is thus an essential step in the optimization of the configuration of the job scheduling system. Third, we plan to gather user feedback in a few months to measure the impact of the proposed modifications as perceived by the users. This will give us a complementary point of view on the benefits of this work and may outline new and unforeseen modifications to make. Finally, we would like to give access to contextualized logs to the job scheduling research community. As mentioned before, this requires more work to reduce the human interventions and to be able to indicate in the logs when operators modified the decisions taken by the system. We believe that the large HTC workload processed at the CC-IN2P3 has specific characteristics which are very different of what can be found in the Parallel Workloads Archive [3] for instance. This will constitute a new source of interesting problems to solve for the research community, whose feedback would benefit to the operation of the CC-IN2P3.

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