Getting ready for Petaflop capacities and beyond:
a utility perspective

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Abstract. Why should EDF, the leading producer and marketer of electricity in Europe, start adding teraflops to its terawatt-hours and become involved in high-performance computing (HPC)? In this paper we answer this question through examples of major opportunities that HPC brings to our business today and, we hope well into the future of petaflop and exaflop computing. Five cases are presented dealing with nondestructive testing, nuclear fuel management, mechanical behavior of nuclear fuel assemblies, water management, and energy management. For each case we show the benefits brought by HPC, describe the current level of numerical simulation performance, and discuss the perspectives for future steps. We also present the general background that explains why EDF is moving to this technology and briefly comment on the development of user-oriented simulation platforms.

1 Simulation background at EDF: a set of competencies and codes backing the operation of a standardized nuclear fleet

EDF background in numerical simulation is deeply rooted in its nuclear PWR program launched in the early 1970s and in its particular responsibilities as an architect and owner-operator. (EDF does not buy turnkey plants but takes responsibility for the global design: it then specifies and assembles different parts provided by various vendors like Areva for the “nuclear island.”) With installed capacity of 63 GWe and 58 standardized nuclear units, EDF boasts Europe’s largest nuclear fleet and 17% of the world nuclear capacity, enabling production of 428 TWh without CO2. It is fully responsible for nuclear safety and for meeting all the stringent rules and controls imposed by external independent bodies to the nuclear industry. From the onset, EDF has chosen to develop a high level of competence in order to successfully manage this program and make the most of operationnal feedback currently exceeding 1200 reactor-years. This was one of the reasons for establishing strong in-house Engineering and R&D teams and has proved useful to constantly stick to the highest degrees of safety while keeping costs under control and operational performance well within the best world standards.

In this context, numerical simulation has been recognized from the beginning as an indispensable tool. It has been used for a long time in such important operational issues as optimizing day-to-day production or choosing the safest and most effective configurations for nuclear refuelling; but most of its advance toward higher levels of performance has been driven by the constant need to better explain complex physical phenomena behind maintenance issues, assess the impact of potential modifications or new vendor technology, and anticipate changes in operating or regulatory conditions.

His permanent progress toward finer and broader physics simulation has been capitalized over the years in a number of codes that make the increase of knowledge quickly transferred from research to operation. Figure 1 shows how Code Aster, a nonlinear structure mechanics code, has been constantly enriched over the past 20 years, with 100k lines of code being added annually over the past ten years.
All those codes, together with the precise knowledge of their capacities and limits, represent precious assets as they not only contain the right physics modelling for the problems that we have to meet but also integrate a high degree of qualification and quality assurance that make them suitable for safety studies. As a consequence the overall pricetag of some of them can reach the 100 M€ line.

Table 1 shows the main disciplinary codes currently in use at EDF in the nuclear domain, most of them being developed by EDF or co-developed with academic or industrial partners. About 150 EDF R&D engineers are directly involved into the development of those codes and associated simulation platforms.

Table 1. Main codes used for nuclear applications at EDF (Ab initio and dynamic molecular material codes have not been included in this list.) CEA: Commissariat à l’Energie Atomique. LAMEL is a joint laboratory with Lille University and EDF.

| Name       | ASTER   | CYRANO | SATURNE/SYRTHES | NEPTUNE | THYC     | TELEMAC  | TRIPOLI     | COCCINELLE | CARMEL   |
|------------|---------|--------|-----------------|---------|----------|----------|-------------|------------|----------|
| Domain     | Non-linear Structure thermo-mechanics | Fuel rod Thermomechanics | Mono-phasic fluid thermo-dynamics | Di-phasic fluid dynamics (CFD) | Di-Phasic fluid dynamics (porous media) | Free surface fluid dynamics | Stochastic neutronics (reference studies) | Diffusion neutronics (industrial studies) | Electromagnetism |
| Owner      | EDF     | EDF    | EDF/CEA         | EDF     | EDF      | CEA      | EDF         | EDF        | EDF/ LAMEL |
| Size (k lines) | 1500    | 150    | 450             | 120     | 100      | 190      | 250         | 200        | 20       |

2. Petaflop computing: opening simulation to quantitative and statistical margin assessment in tenser operating conditions

Most of the above-mentioned codes have been launched 10 or 20 years ago, at times when available computing power was scarce and massively parallel computing unknown in industry. Those obvious
limitations made possible only simplified physics modelling, geometrical approximations, mean value
envelope calculations, involving a number of parameters derived from expertise and matched with
reference experimentations. All of these proved effective in carrying out studies that would generally
stay far from design margins or require moderate optimization. However, those needs are rapidly
evolving into a situation that is bringing a number of structural changes to our company:

- As nuclear assets are ageing, quantitative and credible estimation of operation margins is a key
  factor to curb maintenance costs, allow for performance optimization (through renewed fuel
  management for instance), or help extend a plant’s lifetime.
- More competitive and complex markets, the industrial development of renewable and less
  predictable energy sources like wind power, combined to the urge of minimizing energy
  consumption and peak carbon-intensive production call for renewed and much finer
  management of physical and financial production portfolio and associated risks.
- Climate change and subsequent environmental modifications, floods, droughts, and storms
  together with increasing environmental awareness are bringing up new problems where
  accurate quantitative prediction at both global and local scales is much needed, some of them
  with very high stakes such as increased protection of nuclear power plants and dams against
  floods and quakes or nuclear waste repository design.

Against this tense operating backdrop, we have been convinced from the start that the advent of high-
performance computing (HPC) in the petaflop range would bring new opportunities, not only for
nuclear, but also for a wider range of business applications. As shown in figure 2, we chose to
increase dramatically the computing power made available for our teams in order to boost HPC-based
simulation and demonstrate that thinking petaflop was no R&D utopia but could provide quick return
for business.

Two years after we installed our first 23 Tflops IBM BG/L machine, and only months after we added
another 100 Tflops BG/P, this vision has been confirmed by facts. The following paragraphs will
report on some of the practical advances that have been already attained and the perspectives that they
open for future, and even more ambitious applications. As shown in figure 3, we have started work
along three technically distinctive “HPC paths”, shortly described below, which roughly correspond
to increasing complexity and costs.

![Figure 2. Evolution in computing power at EDF (Tflops).](image-url)
1. The first and easiest move that we made consisted in using HPC parallel brute-force calculations to provide statistical coverage with unchanged industrial-grade codes, through thousands of parallel single simulations (representing as many combinations between parameters values, events, operating conditions), thus allowing for uncertainties management and parametric studies. These kinds of high-throughput approaches represent a broad spectrum of opportunities as they enable to switch from single, often worst-case calculations to stochastic methods that give more insight on rare events distribution. However, even if this category of completely uncoupled calculations has the smallest cost tag, first experiments show that it can challenge both the code itself (which is tried against a much wider domain) and the parallel architecture where data flows management have to be carefully designed.

2. At the same time we started to advance on the more classical path of tightly coupled calculations in order to extend the use of existing “best estimate” simulation technology to systemwide analysis, with the relevant physical space and time coverage. The intention was to move from the calculation of average operating values (the kind of calculations that were made at the design stage with sometimes heavy margins to cover uncertainties and approximations) to the evaluation of much finer phenomena and punctual extrema in space and time that can yield precious information on operating margins. A typical example, described later, is extending the use of 3D-CFD to simulate the flow of water within a complete nuclear vessel with submillimetric prediction of temperatures and pressures across time. The main cost for this second type of HPC benefits is bringing the best estimate codes to the strong-scaling capacities that are necessary to keep calculation times within acceptable limits. On top of that, production of the fine meshing required and visualization of the large datasets produced become nontrivial tasks, calling for specific R&D efforts.

3. The third approach, which we are only beginning to touch on, involves not only scaling existing codes but developing new HPC simulation technology, currently unavailable because meaningless in the absence of large computing power. Closely coupled multiphysics simulations as well as complex optimization fall in this category. This type of development is still at initial R&D stage but will obviously yield the biggest medium-term returns. Of course, categories 2 and 3 can, and often must, be combined with stochastic simulation: initial petaflop-grade requirements can then quickly turn into near-exaflops needs.

3 Nondestructive testing
Nondestructive testing is a major issue for nuclear operation. Annual costs range well over 100 M€/year, as numerous tests are systematically conducted during maintenance operations to ensure...
and demonstrate the safety of critical parts of plants like the nuclear vessel, steam generators, and associated piping. It is therefore essential to do the following:

- Demonstrate the ability of the various procedures (radiographic, ultrasonic or eddy-current)
- Detect potential defects
- Optimize preparation in order to guarantee safe, reliable, and timely operation during the very constrained outage schedules (any problem occurring at this time can generate high-costs delays)

This is usually achieved through preparatory experiments carried out on physical models by highly skilled engineers. However, this approach has met with a number of difficulties:

- Some models can be costly to design because of difficulties to engineer faithful geometrical shapes and defects.
- Selecting a methodology for a particular control requires a choice between several options and testing robustness against a number of uncertain parameters that are difficult and costly to reproduce extensively during the experimental phase; radiographic testing, for instance, means selecting type and position of source (selenium, iridium, cobalt, etc.) and type and position of film, taking into account possible misalignments or incomplete knowledge of the precise state of installation under control (water level in the pipes, etc.).
- Physical models do not easily allow for parametric study on the size and location of defects.

A first attempt at using high-performance simulation for radiographic testing has proved successful in overcoming these difficulties and improving performance while reducing costs and delays [1]. Simulation here means simulating the thousands of billions of photons emitted by the radioactive source used in a real test, calculating direct and scattered paths, and imaging the impacts at the simulated film level as, represented in figure 5.

![Figure 5. Simulated radiographic testing showing paths of gamma photons in a pipe.](image)

This is a comparatively easy job as it requires only a simple Monte Carlo algorithm (particle paths are independent, thus allowing “natural” parallelization of the code) with a boxed-in device recording photons as they reach the film. (The main result of the calculation is the ratio between direct and scattered radiation, which is a characteristic data for a given test configuration, equivalent to a signal to noise ratio; most photons don’t reach the film; scattered photons that reach the film blur the crisp image from direct radiation and limit the capacity to detect defects. This ratio is extrapolated by smoothing from a partial calculation.) However, a complete calculation would have to deal with up to $5 \times 10^{16}$ photons, which is currently not feasible for lack of a petaflop computer fully used during several months! In practice, we validated an extrapolation method from a semi-reference calculation carried out with our Moderato code, using 1200 billion photons and 145,000 CPU-hours on 1000 cores of an IBM BG/L. This enabled the simulation of the most challenging cases, such as preparing for the inspection of bimetallic connections in the coolant systems. The difficulty here stems from the panoramic exposure and the extreme thickness of the part, 100 mm steel piping. A 150-billion photon calculation was run in less than one day on 1000 BG/L cores and included source sensitivity studies such as cone opening and type.
But this is far from being the end of the story. Similar advances are expected for ultrasonic testing [2], which is used to control many critical parts of the primary circuit (welds, core internal surface, etc.). The challenge is to move from a mostly 2D analysis, enough to deal with fatigue cracks, to full 3D simulations, able to represent the interaction with complex ramified and disoriented stress corrosion cracks. We used the 3D code ATHENA, developed with the help of INRIA (the French national institute for research in computer science and control). It uses an explicit finite-difference scheme to solve the 3D elastodynamic equations, a fictitious domains method to solve the crack-wave interaction problem, and PML (Perfectly Matched Layers) to model infinite domains. This leads to problems with up to 10 billions meshes (at least 10 meshes are required per wavelength – 0.5 mm at 2 MHz), or several tens of billions of degrees of freedom, and will need executions on more than 20,000 cores to keep response time under two days. Athena parallelization is under way with INRIA, and the appropriate level of performance should be achieved during 2009.

4  Nuclear fuel management

EDF reloads about 50 of its nuclear reactors every year. Standardized reload assemblies are used for each plant type (900 MWe, 1300 MWe, and 1450 MWe) called “reference fuel management,” defining the uranium enrichment to be used (enrichment varies from 3 % to 4.5 % $^{235}$U), leading to 12 or 18 months cycle length, and the number of fresh fuel assemblies to be loaded. An industrial calculation chain enables to perform reload design and safety studies [3]. Gaining flexibility in loading patterns would allow for better adjustment of cycle lengths to market needs and yield significant performance improvement of the whole nuclear fleet. However, assessing the safety of those new patterns requires an increased number of full core transient calculations, often complex, difficult, and expensive.

Figure 6. Refuelling a nuclear power plant (left); simulation result showing the most solicited assemblies within the core (right).

We currently are studying a different option that replaces transient calculations by a bounding approach, resulting in much simpler, static core simulations but repeated a very large number of times in order to cover the full combination of parameters that define possible states of the nuclear core at any given moment. The main values to be explored are the following:

- burn-up levels (at least 3 or 4),
- xenon (which results from iodine radioactive decay and is a neutron absorber) three-dimensional distributions (several tens),
- power levels (typically 10), and
- control rod positions for each group of rods (several hundreds).

Altogether, up to 200,000 full-core static computations are necessary, using the neutronics code Coccinelle, each one calculating the 3D power distribution in the core (1-minute calculations on a
standard core). Preliminary simulations have been run on 400 cores, lasting roughly 20 hours. So far, these studies have been conducted for R&D purposes only but, in the short term, might join the set of industrial tools EDF uses for preliminary safety analysis. In the long term, they might even be used for demonstrating the safety of individual reloads: computation time will have to be brought down to less than one hour, a task that should be comparatively easy with about 10k cores. But the most difficult challenge will be to demonstrate a very high level of hardware and software reliability, as required for field operation.

These kinds of studies are typical of a large set of high-stakes applications where the massive parametric calculations capacities brought by HPC must be carried out “against the clock”: in a matter of days for engineering-type processes, and in a matter of hours or minutes for field operation processes.

5 Mechanical behavior of nuclear fuel assemblies and nuclear vessel internals

Precise estimation of thermo-mechanical effects in the nuclear reactor is of paramount importance for such high-stakes safety and maintenance issues as nuclear vessel lifespan, axial stability of nuclear assemblies, or premature wearing of fuel rods induced by fretting (this does not count the major thermo-mechanical effects induced by neutronics reaction within the fuel rods, which constitute a separate study field). This kind of problem requires more and more accurate calculations of hydraulic flows within the core and make it highly desirable to move to 3D CFD codes applied to the full geometrical complexity of the internal structure of the vessel. HPC is a key enabler to apply those “best estimate” codes at such a complex level and reach a better management of conservative assumptions associated with more simple flow modeling (like porous media codes).

Figure 7. Flow simulation in complex geometries within a nuclear vessel allows fine temperature evaluation at screw level (top right).

One of the first thermal hydraulics applications of HPC at EDF was the precise evaluation of mechanical properties of hundreds of screws used to hold the peripheral shielding part in the nuclear core. Fine calculations of temperature-induced mechanical constraints under the screw head implied thermo-hydraulic simulations spanning not only the full multimetric height of the core but also the submillimetric scales at the screw level, taking into account complex geometries as can be seen on figure 7. This first calculation was run in 2006 on 200 processors over 11 days.

However, much more refined calculations are necessary in order to solve even more complex issues such as the precise fuel assembly and fuel rods mechanical load induced by water flow within the core. In 2007, a better understanding of the effect of mixing grids (millimetric details shown in figure 8) on the mechanical loading in fuel rods was made possible thanks to a CFD stationary flow calculation around part of a fuel assembly. This involved 100 million cells meshing and 1 month of calculation with the code Saturne on 8000 BG/L processors.
Figure 8. Submillimetric meshing allows for fine evaluation of mixing grids effects on the water flow in fuel assemblies.

But this level of detail should also be reached at the full core level: this would allow for instance to account for intrinsic dissymmetries brought by different geometries of different vendors assemblies used at the same time in a single nuclear vessel. We anticipate that this full-scale simulation, which may require as much as a 10-billion cell meshing and several weeks computing on a 10-petaflop computer, will become possible in about five years. Combined with similar changes in neutronics simulation, this would yield significant qualitative changes in the way safety and performance studies can be carried out for nuclear vessel environments.

6 Water management
In France, 70 percent of surface waters flow through an EDF dam or by an EDF plant. Water management is a strategic issue for both protecting powerplants against environmental phenomena (dimensionning dykes to resist exceptionnal events like the December 1999 storms in Europe) and for managing such effects as the dilution of warm water from nuclear plants in the rivers (excessive temperature rise can force plant shutdown in hot summers). In addition, complex underground water flow is a key aspect to nuclear waste repository design, a very high-stakes project currently under study in France.

The multidimensional simulation set of tools TELEMAC has been designed and used for more than 20 years to conduct such studies. It allows the modeling of the main hydraulic and environmental phenomena such as tides, floods, waves, transfer of pollutants, and sediments in surface and underground waters. However the growing importance of environmental issues is calling for much more complex studies that may involve both long-distance and local three-dimensional phenomena (pollutant discharges, thermal plumes, sediments transportation, etc.), turbulence and stratification (soft water discharges of the Durance river dams into the salty water Berre Lake), or very complex surface flows (waves breaking against dykes or offshore windmills). Telemac is currently being adapted to HPC in order to provide the dramatic performance increase that is needed to tackle those new challenges, as the following example will show.

Following reassessment of extreme meteorological events, a number of dam spillways must be adapted or added to accommodate worst-case floods that can be twice as severe as in the initial design. Very complex flows occur at the spillway level and at the bottom of the dam. Accurate prediction is necessary to ensure that the particular design can indeed provide the expected extra throughput and that the dam bottom structure will not be affected by extreme turbulence. Those studies have been
started with physical-scale models like the one in figure 9 that was until recently the only way to represent such highly turbulent free-surface flows (experimental studies take as much as 12 months). However, HPC is rapidly changing that by enabling an alternative simulation method, called SPH, or smooth particles hydraulics; SPH is a Lagrangian approach that models complex water flows by a set of macroscopic particles interacting with each other through repulsive forces and displaced according to the impulse received. The approach until recently had remained confined to much smaller test cases for lack of computing power.

In less than six months, the corresponding code Spartacus 3D has been ported to BG/P through a partnership with IBM and its scalability improved to a level where it can now accommodate the number of particles required for this kind of industrial-grade study. First runs with 6 million particles have just been achieved on 8000 cores, simulating a reference dam break. The encouraging results should lead to a full-size simulation of the Goulours dam complex spillway at the end of 2008, for validation purposes, opening the way to fully numerical studies (including parametric design) in the near future [4, 5, 6, 7].

![Figure 9. Physical model of Goulours dam showing complex flow from spillway.](image)

## 7 Energy management

One of the most challenging problem EDF has to solve, and also one with the most immediate and heavy societal and financial stakes, is constantly balancing demand and production with minimum risk of not meeting demand, minimum environmental impact, and minimum costs. At a given moment, decisions have to be made regarding which production units to use, with particular emphasis on the proportion coming from hydraulic plants. Always choosing to use near-zero-cost water stocks from the dams (when available) is far from being the best decision when considering the consequences over one or two years. It is therefore necessary to formulate a more elaborate strategy that optimizes current decisions against many possible scenarios for the future, up to three years ahead. This is a tremendously complex stochastic dynamic programming problem, where computing needs grow exponentially with the number of energy stocks and with uncertainty factors.

As a consequence, current models and algorithms (e.g., the Bellman algorithm) can use only four energy stocks (three aggregated water stocks and one stock of demand-side options that can be activated to off-load consumption peaks) in order to deliver results in the limited time frame expected by field operators (overnight is a maximum). Taking into account many more stocks is necessary to reach a better optimization, for instance: more water stocks (corresponding to a finer decomposition of existing ones), fuel stocks, futures bought on the market, SO₂ maximum emissions, all those parameters being currently managed by experts outside the main optimization loop. In addition there is also a need to better represent the many types of constraints that limit operation of the various units such as start-up and shutdown ramp constraints, minimum operating and stopping delays, dam dependencies in a hydraulic valley.

Massive HPC power, combined with algorithmic efforts to reduce the “curse of dimensionality” of the Bellman algorithm, is currently being tested to evaluate the benefits of a 10-stocks optimization allowing for dynamically hedging with electricity market available futures.
contracts. This optimization, over a of 1.5 years with 1-day time steps, will use 32,000 BG/P cores to keep processing time under 3 hours. Depending on the improvement desired over current methodologies, this kind of application will clearly require petaflops-class computing in the near future [8,9].

8 End-user simulation environment
Advancing individual solvers performance is not enough to bring high-performance simulation to the end-user. Each community needs a much broader set of tools in order to conduct industrial studies: CAD, mesh generation, data setting tools, computational scheme editing aids, visualization, and so forth.

In early 2000 EDF, together with CEA and other industrial and academic partners, started the development of an integrated toolbox Salome [10,11], with the following aims:

- Reduce the cost of complex simulation platforms by mutualizing a set of common tools: pre- and postprocessing, calculation distribution and supervision, and so on.
- Boost performance through easy integration of multiple solvers for multiphysics studies (via a common data model).

Salome contains about 500,000 lines of code (85% C++, 10% Python) and has been used since 2007 for major applications such as the structural mechanics platform SimuMeca, which serves a community of about 200 in EDF Engineering and R&D Divisions.

Salome’s technical prerequisites rely on widely used open source solutions. Computational results are stored in HDF5 format (or XML for small pieces of data) in order to ensure portability and efficiency. Communication between user interfaces, computational engines, and codes is performed with CORBA, which makes them interoperable whatever the implementation programming language or their localization. A common data model and associated libraries make possible structured data exchange, allowing better modularity between components. Graphical representation of input data (geometry, meshes) and results is made with the VTK visualization library, which is easy to use and offers a high level of abstraction. In the near future, Paraview will also be included in Salome. Data manipulation, computation supervision, and exploitation of simulation results may be done through a graphical interface or via a Python script. These two ways of performing simulations, thanks to the Salome communication bus, enable the Salome user to interactively define its study via the graphical interface and then to quickly automate the simulation process by reloading the Python script generated by Salome. Python also offers advanced users numerous services for complex studies or parametric computations.

If Salome has been proved to be well adapted for sequential and moderately parallel simulations it is evolving in order to support massively parallel computing. Work is under way on what we consider three critical components:
### Mesh generation

In 2007 it took several months to produce the \(10^8\) cells mesh for the simulation of part of a fuel assembly with the CFD code Saturne, compared to “only” 1 month of calculation needed on 8000 BG/L processors. Generating a \(10^{10}\) cells mesh as targeted in 2015 requires future meshing tools to provide parallel meshing, automatic hexahedral meshing, mesh healing, CAD healing for meshing, and dynamic mesh refinement. A collaboration with Distene (Spin-off initiated by INRIA) is engaged on these issues.

### Visualization

We are currently putting together a 6 by 3 meter, 23 Mpixels Power Wall, together with parallel visualization tools and clusters, in order to boost our visualization capacities of the most advanced simulations. However, the sheer volume of data produced by petaflop calculations, storage and network limitations, and multisite teams make it necessary to further advance R&D in a number of areas [12]. Under the CARRIOCAS project and the SCOS project we have started work on remote and collaborative multiuser visualization, parallel visualization, and parallel and distributed file systems.

### Supervising and code coupling tool

In 2006, EDF and CEA started development of YACS, a new generation of supervisor, intended to handle a parallel multiphysics coupling scheme named PACO++ [13], developed by INRIA through a portable parallel extension to CORBA. PACO++ defines a parallel object as a collection of identical CORBA objects whose execution model is SPMD (single program multiple data). Special attention has been given by EDF team to the support of distributed arguments. The arguments can be distributed on both the client and the server sides. PACO++ provides mechanisms (static and dynamic) to specify the data distribution on both sides. Since the two data distributions may differ, data redistribution may be required during the communication between the client and the server.

### 9 Concluding remarks

As we have seen from the preceding examples, high-performance simulation for our industry is not just a possibility for a hazy and distant future: as of mid-2008 work is under way on 10 major cases where this kind of technology opens clear and unique opportunities. One of them is already in operational use; three more should yield industrial-grade results this year. HPC has been raising opportunities across a large scale of business activities. Far from being confined to nuclear operation, it is now being seriously considered for applications as different as renewable energy development (advancing photovoltaic performance), marketing (pricing new services), or financial risk management.

This process started with a decision to bring HPC machines to R&D teams, even though no detailed needs for such supercomputers was available. Building from this initial move, a few computer science engineers and applied mathematicians, together with some advanced numerical physicists, succeeded in “spreading the HPC word” within the company by showing first results meaningful for business decision makers. These efforts in turn made it obvious that this technology would not only improve existing processes but could change them altogether for more radical optimizations. Innovative thinking is now well on the way, fueled by a better perception of the new HPC capabilities and perspectives.

At the same time HPC raised new concerns:

- Are underlying models sound enough to make sense when stretched to new performance levels? How to extend qualification domain when experimental data is scarce or very costly to access?
- What level of model refinement is coherent with unavoidable remaining uncertainties?
- How can we build decision-makers’ confidence when models and calculations complexity make it more and more difficult to check against one’s own intuition? What kind of new expertise should be developed to secure a broader use of those new capabilities?
- At which time horizons and costs can we expect the computing reliability and service level necessary for a reliable use in the field?

Most of those questions remain open today and we try to handle them step by step through practical feedback in real operational situations. On the technology side, besides pre and post processing issues
raised by the huge increase of data, we are facing the immediate problem of scaling existing codes on a very large number of cores. Figure 11 shows that three applications are already using 10k processors or more.

\[\begin{array}{c|c|c|c}
\hline
Year & 1k-10k & >10k \\
\hline
2006 & 1 & 0 \\
2007 & 2 & 1 \\
2008 & 3 & 2 \\
\hline
\end{array}\]

**Figure 11.** Number of applications using more than 1k processors.

This has been achieved only two years after we bought our first BG/L machine, through both in-house efforts and partnerships with academics and IBM to port and scale our codes. However successful we have been in this initial period, we know that future advances may be at a higher cost:

- ASTER, for instance, our structure-mechanics code, hardly scales today on more than a few tens of processors, because we have not yet found a general enough solution that would match the very wide array of its modeling capacities, and the direct solving methods that give it its industrial-grade robustness. (Three “nonintrusive” ways of scaling ASTER are currently being looked at with academic partners: at the solver level, testing parallel direct solvers for large, sparse matrixes; at the modeling level, implementing a domain decomposition method called FETI (Finite Element Tearing and Interconnecting); and at the simulation control level using a code-coupling library adapted to parallel computing to coordinate many ASTER runs within a domain decomposition approach.)
- On the other end, our fluid dynamics code Saturne that currently scales over 10 k cores, will have to support runs on 100 K or possibly one million cores in order to yield expected performance on already identified challenges. At this level of parallelism we know that we will have to deal with hardware fault tolerance, potentially heterogeneous/hybrid computing nodes, hierarchical multilevel memory, and critical load balancing.
- Dealing with large domains (billions of cells, tens millions of particles), also raises numerical stability and precision computation problems that could induce algorithmic and numerical solver adaptations, as we have already discovered.

Solutions to this kind of generic HPC obstacle lie very much in the hands of academic research, universities and computer vendors R&D. EDF is willing to take part in this effort through direct R&D inputs and partnerships with the relevant initiatives and communities in Europe and worldwide, as well as by publicizing our industrial cases and focusing attention on the scientific challenges that they pose, some of which we believe can be nearly as daunting as the most difficult problems in more fundamental energy research.

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