Stochastic control optimization & simulation applied to energy management: From 1-D to N-D problem distributions, on clusters, supercomputers and Grids

Stéphane Vialle, Xavier Warin, Constantinos Makassikis, Patrick Mercier

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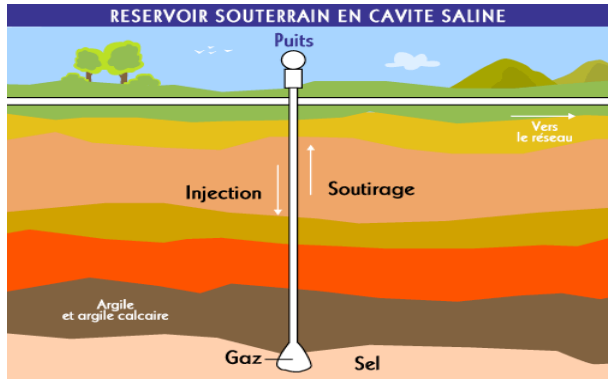
Project 1: the first steps

“One-dimensional stochastic optimization: application to gas storage valuation”

1 – First Motivations and Objectives

For technical, financial and legal reasons, energy trading companies need to have energy stocks.

→ For example: gas storage.

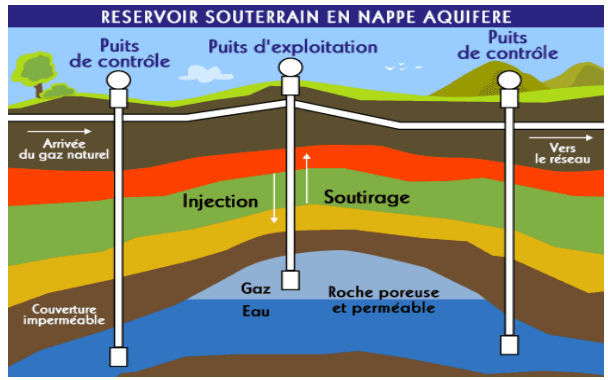


These are expensive investments!

→ How to optimize the management of gas storages?
→ How to compute the renting price ?

Computation of a « gas storage valuation »:

- compute the « value » of an investment project about a gas storage cavity,
- compute profits and risks associated with the ownership of a gas storage cavity, considering an open energy market.



2.1 – Resolution method

- Instantaneous profit: $\begin{cases} < 0 \text{ when injecting gas (we pay this gas)} \\ > 0 \text{ when withdrawing gas (we sell this gas)} \end{cases}$

$$\phi(t, S_t, I_t), \text{ with } \begin{cases} S_t : \text{gas price at time t} \\ \mathrm{I_t} : \text{regime (injection, withdrawal, nothing)} \end{cases}$$

- Expected profit from t0 maturity (T):

$$J(t_0, s, c, i, u) = \mathbb{E}\int_{t_0}^{T} \phi_{u_r}(r, S_r, I_r).dr$$

includes random variables

u : stragegy of gas storage management

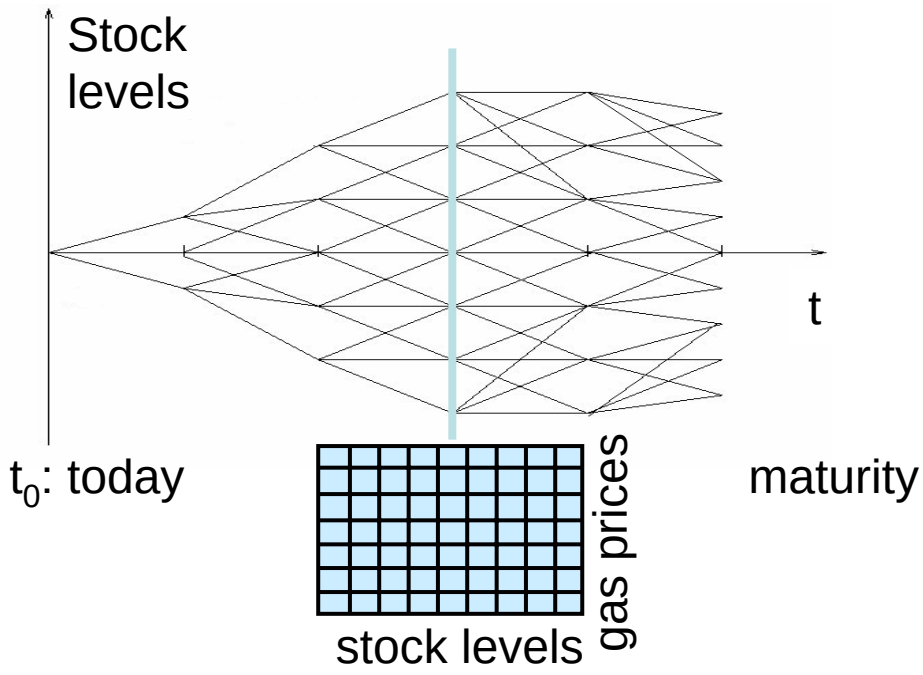
- Looking for a strategy *u* leading to the maximal profit *J**:

$$J^*(t_0, s, c, i) = \sup_{u \in U_{t_0}} J(t_0, s, c, i, u)$$

2.2 – Dynamic Programming Algorithm

Computation of the maximal profit and associated strategy:

- using a « backward dynamic programming algorithm »
- fixing a strategic scenario at maturity
- considering 2 main variables:
  - ✓ admissible stock levels
  - ✓ possible gas prices: “alea”
- computing a 2D table of possible maximal profits at t_n function of:
  - ✓ possible profit 2D table at t_{n+1}
  - ✓ action from t_n to t_{n+1}
- at t_0 (today) the algorithm joins the current stock level and gas price.



Results: 1) Expected (maximal) profit from t_0 to maturity,
2) List of actions to do at each time step in any case

2.2 – Dynamic Programming Algorithm

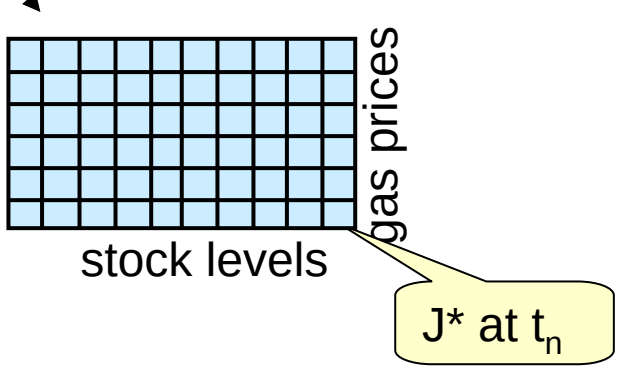
Backward dynamic programming algorithm:

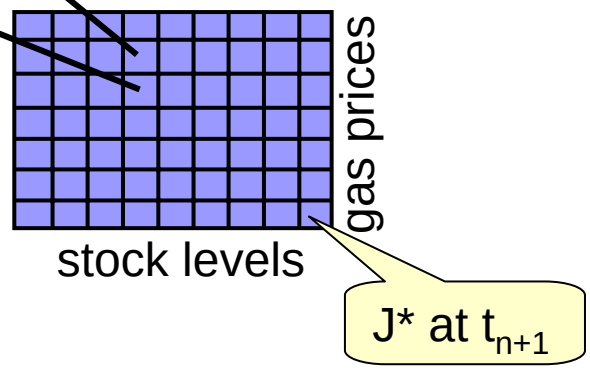
$$\text{for } t \leftarrow (M-1)\Delta t \text{ to } 0$$

$$\left|\begin{array}{l} \text{for } c \in \{\text{admissible stock levels}\} \\ \quad \left|\begin{array}{l} \text{for } s \in \{\text{possible price levels}\} \\ \quad \tilde{J}^*(s,c) \leftarrow \max\begin{pmatrix} -(a_{in}s + K_{in})\Delta t + \mathbb{E}(J^*(S_{t+\Delta t}, c + a_{in}\Delta t) \mid S_t = s), \\ +(a_{out}s - K_{out})\Delta t + \mathbb{E}(J^*(S_{t+\Delta t}, c - a_{out}\Delta t) \mid S_t = s), \\ -K_s \Delta t + \mathbb{E}(J^*(S_{t+\Delta t}, c) \mid S_t = s) \end{pmatrix}; \end{array}\right. \\ J^* \leftarrow \tilde{J}^*; \end{array}\right.$$

Looking for the maximal profit among 3 cases:

- injection
- withdrawal
- doing nothing





2.3 – Price models (“alea”)

3 models of gas prices have been considered:

- **« 1-factor Gaussian »:**
  - considering one short-term random variable to model spot prices
  - evolution of prices without any jump
- **« 2-factor Gaussian »:**
  - considering one short-term and one long-term random variables
  - evolution of prices without any jump

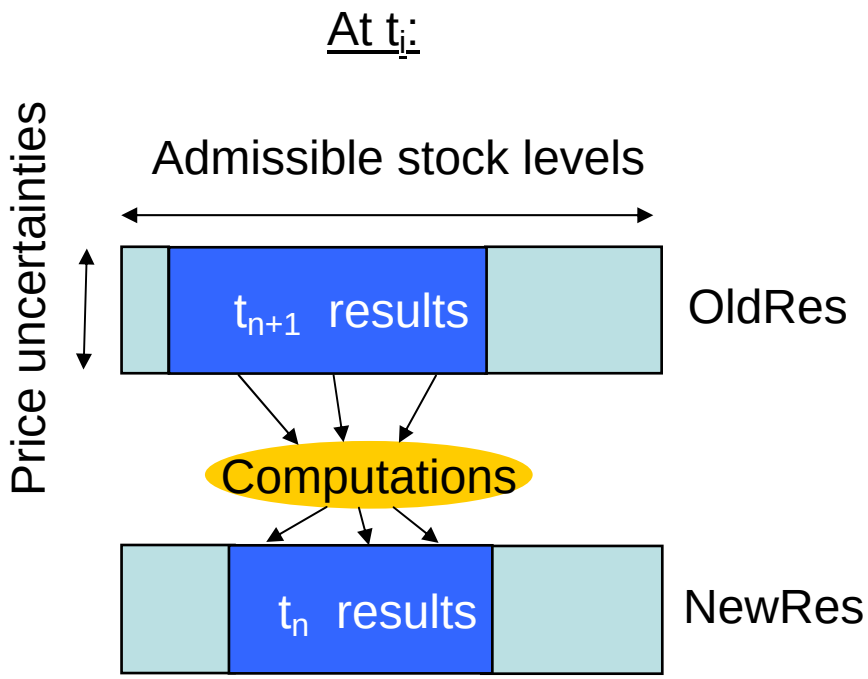
→ Computation of the expected profit ($\mathbb{E}$) using trinomial trees

- **« Normal Inverse Gaussian »:**
  - “jumping” model
  - to model the impact of phenomena leading to brutal change of gas price

→ Computation of the expected profit ($\mathbb{E}$) by solving a complex PDE (computed with an iterative algorithm)

3.1 – Parallelization strategy

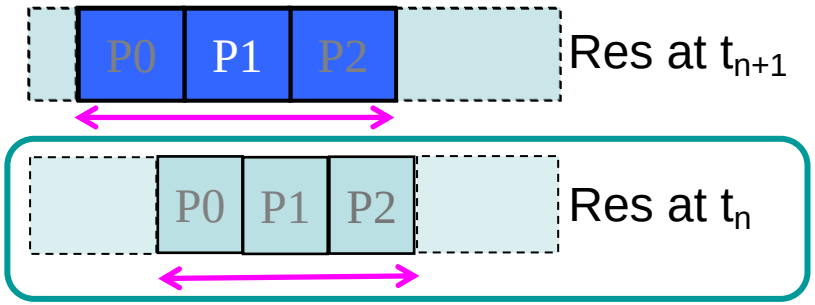
- **At each time step** two tables are used:
  - ***NewRes*:** for storing results of ongoing time step t_n.
  - ***OldRes*:** results of time step t_{n+1}.
- **Problem 1:** stock levels of interest are contiguous but with variable bounds at each time step!
- **Problem 2:** complete set of data is too large to be stored on one node!

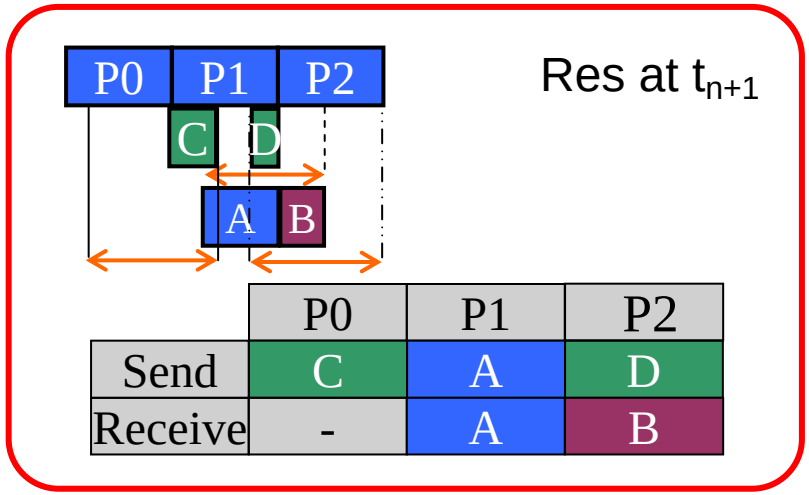


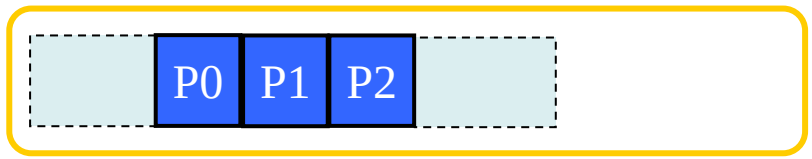
Strategy:

- Distribute *OldRes* and *NewRes* tables of data and computations
- Compute and route only required parts of *OldRes* table

3.2 – Communication scheme







Example on P1:

1) Determine the **new bounds and distribution of computations at t_n**

2) Determine **data required at t_n** by P1: data to receive

3) Determine **data to send** by P1

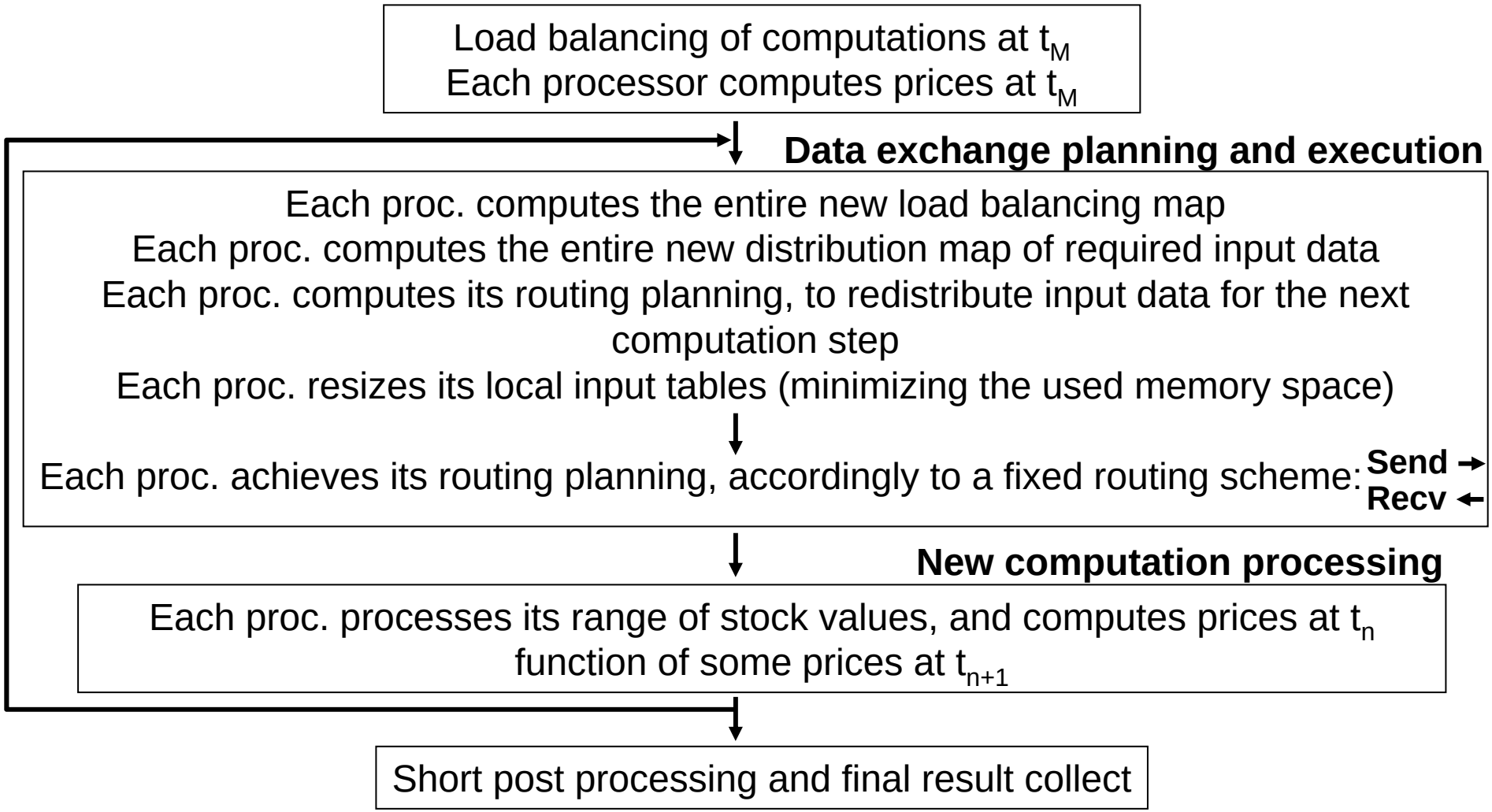
} **Routing plan**

4) Allocate optimal in size **data structures**

5) Make **communications** according to routing plan with MPI library

6) Compute Res at t_n

3.3 – Distributed Algorithm



3.4 – MPI – C++ implementation

Implementation strategy:

To speed up: parallelization and overlapping of all communications during the execution of one routing plan,

but computations and communications can not be overlapped

To size up: avoid extra communication buffers

→ Use of MPI_Issend / MPI_Irecv / MPI_Wait routines

→ Memory management to allocate strictly required memory at each step

Others communication routines have been experimented…
… “Issend / Irecv / Wait” appeared to be the fastest.

And: uses Blitz++, Boost and Clapack libraries

4 - Testbeds

3 distributed architectures:

- Small and cheap desktop-PC cluster:
  - 32 nodes: 32x (1 mono-core Pentium-IV 3GHz, 2GB of RAM)
  - cheap Gigabit Ethernet network : 2x 24-port switches, double linked
- Medium sized blade-PC cluster (a cluster of Grid'5000):
  - 72 nodes: 72x (2 mono-core Opteron 2GHz, 2GB of RAM)
  - fast/normal Gigabit Ethernet network (1 large switch)
- IBM Blue Gene/L (EDF supercomputer):
  - 4096 nodes: 4096x (2 mono-core processors, 700MHz, 1GB of RAM)
  - Several fast interconnection networks

3 benchmark programs:

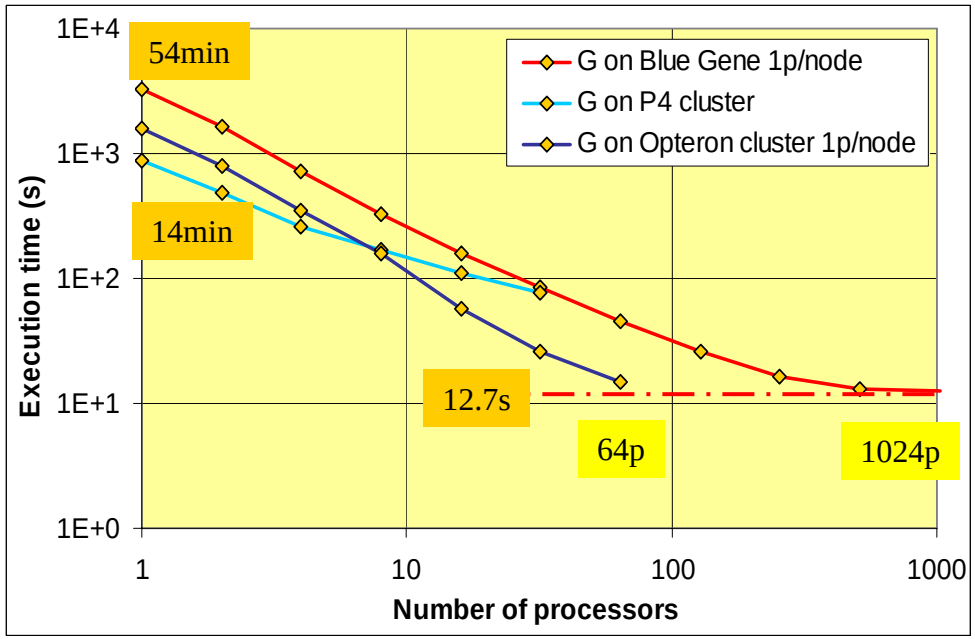
- with "1-factor Gaussian" price model → needs speed-up
- with "Normal Inverse Gaussian" price model → needs speed-up and size-up
- with "2-factor Gaussian" price model → needs size-up and speed-up

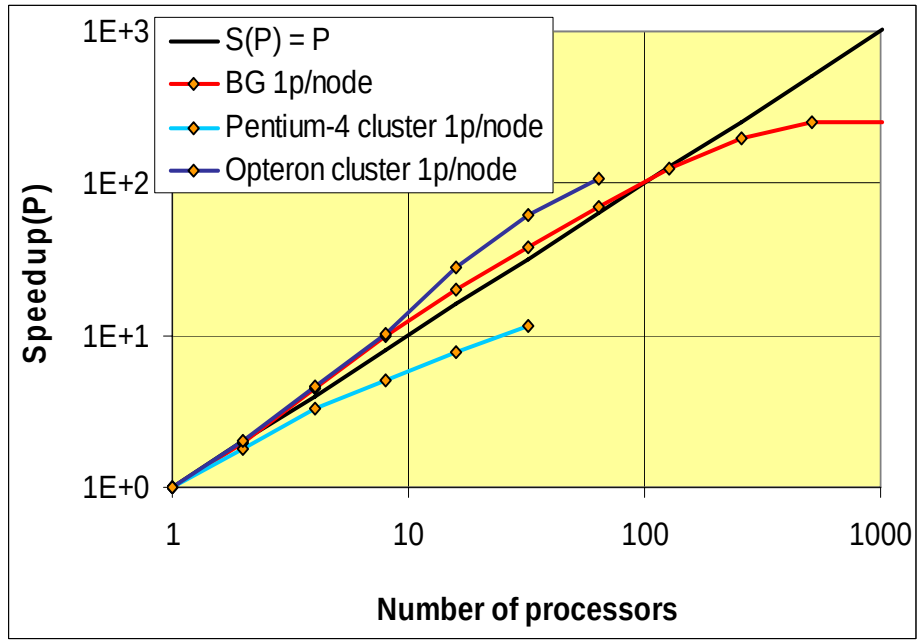
Experimental performances

5.1 – 1-factor Gaussian model

- Small problem!
- Good scaling on BG/L and on blade PC cluster, and final speedup close to 254 and 107
- Bad scaling of the small cluster (with cheap Gigabit switches)
- Some superlinear speedup due to cache memory increase (?)

- Using 2 proc. per node leads to poor performances…
- Finally, BG/L appears a little bit faster than the blade PC cluster.
- But both seems to reach their scalability limit on this small problem.

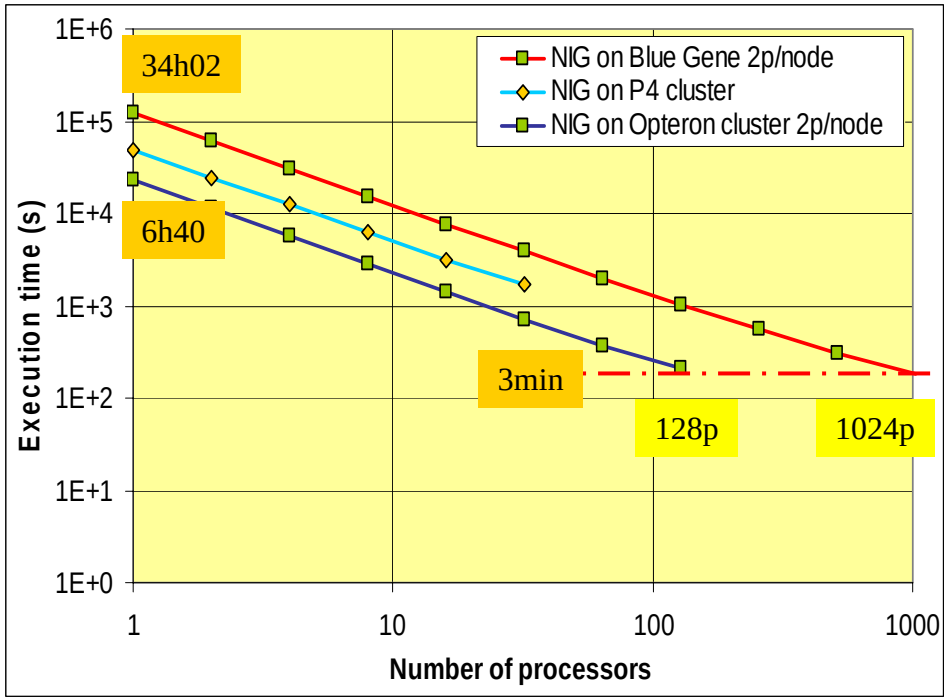


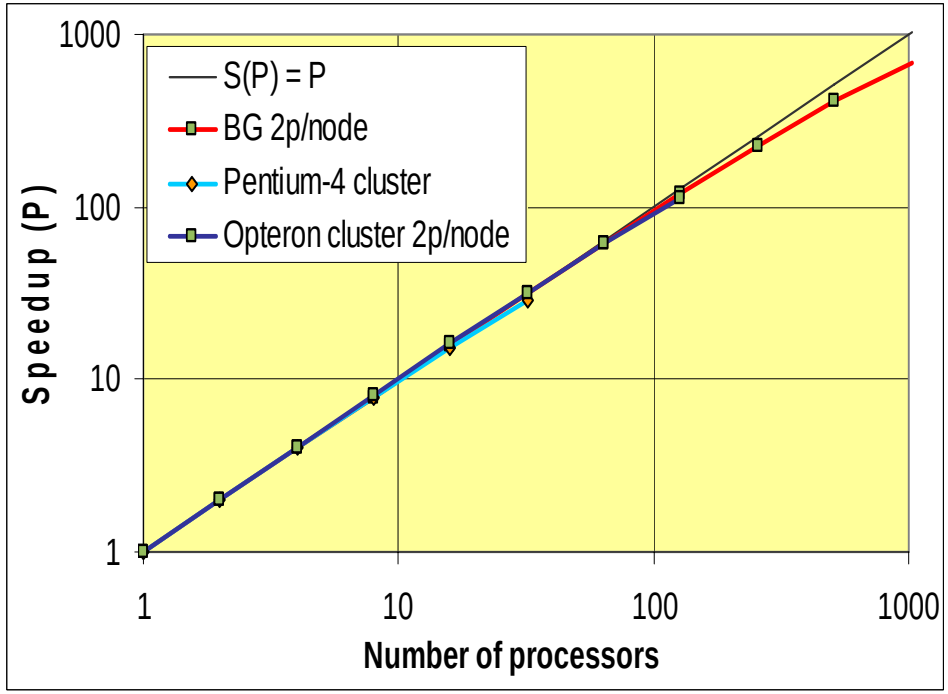


5.2 – Normal Inverse Gaussian model

- Long execution time problem
- Higher computation/communication ratio (than for 1-factor Gaussian model)
- Good scaling and final speedup (680, 29 and 110) on all parallel machines

- Using 2 proc. per node does not disturb the performances
- Finally, Blue Gene appears as fast as the blade PC cluster
- Speedups are very close of the ideal speedup



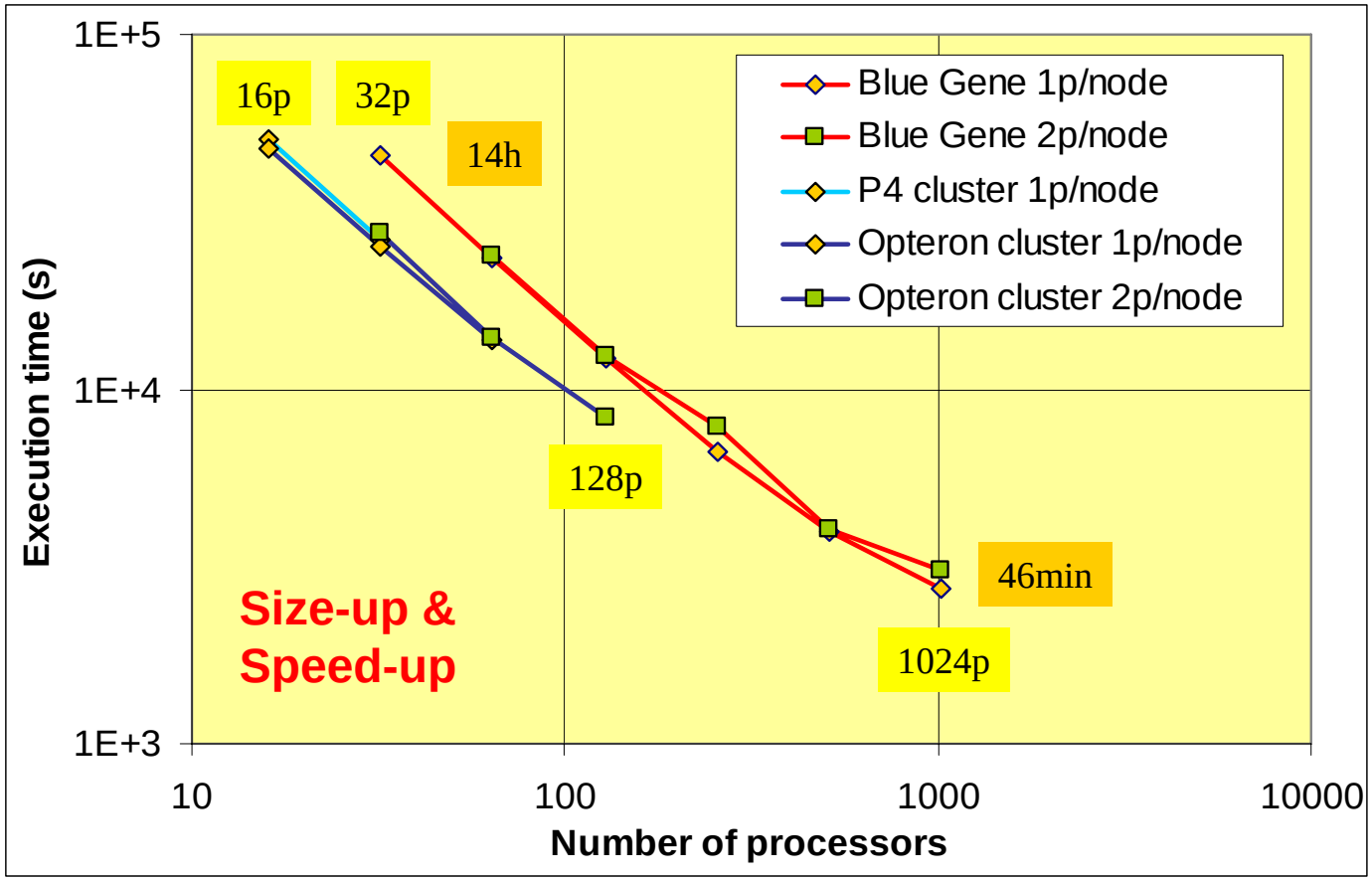


5.3 – 2-factor Gaussian model

- Large size and long exec. time problem: at least 11GB of memory (for sequential runs)
  → impossible to run on 1 proc. and to compute rigorous speedups
- Highest computation/communication ratio (of the 3 benchmarks)
- Good scaling on all parallel machines

- Using 2 proc. per node does not disturb (too much) the performances.

- Blue Gene/L achieved better performances, taking advantage of its very large number of processors.



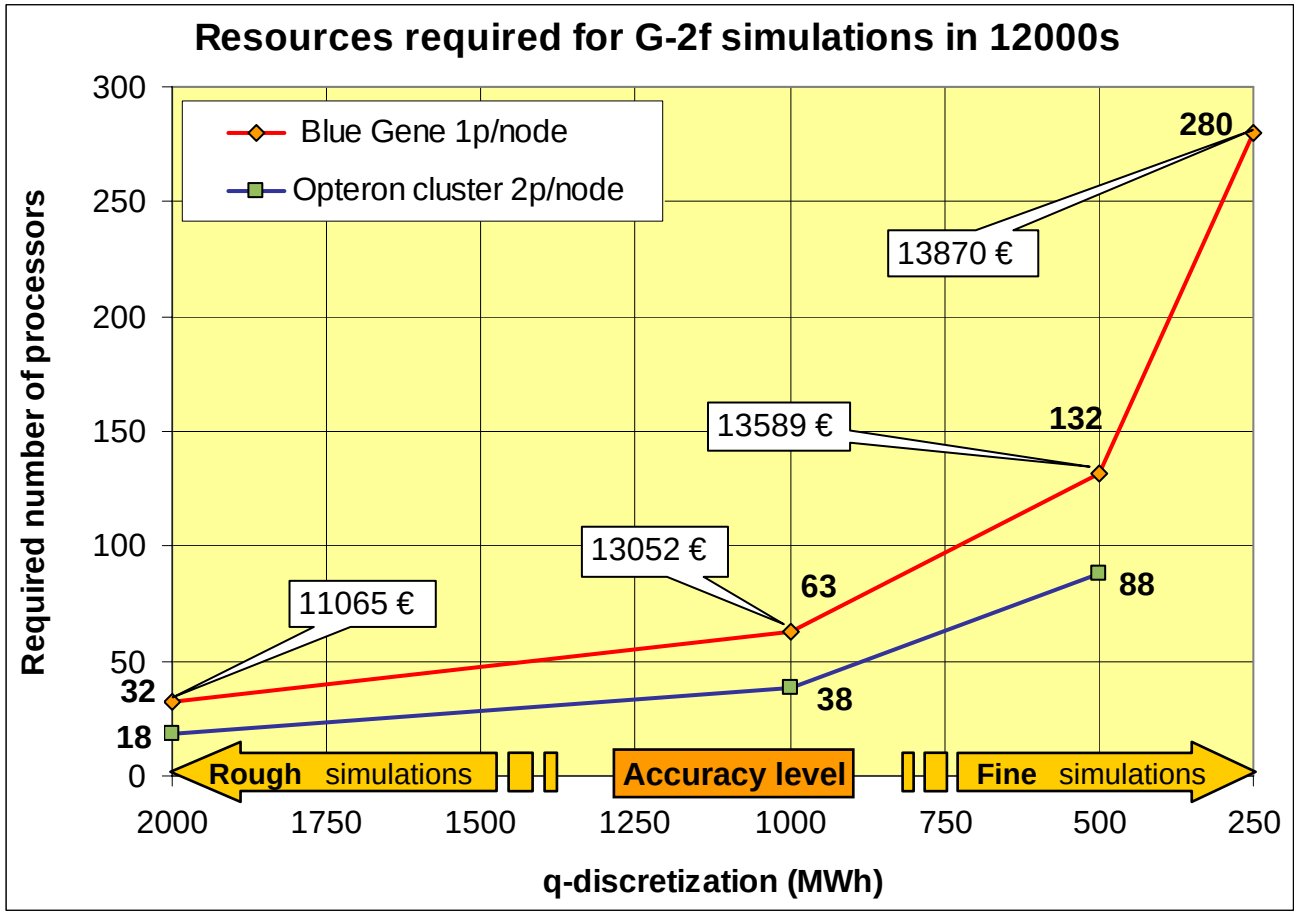
5.4 – Scalability experiment

- Previous simulations used a *q-discretization* factor of stock level equal to 500MWh.
- In order to run a simulation in limited time (before making a deal) and not to monopolize too many computing resources, it is necessary to adapt to the required accuracy.

→ New scalability test of our parallelization.

Example:

Successful identification of the right nb. of proc. to run the parallel simulation in 12000s (3h20) function of the accuracy factor *q-discretization.*

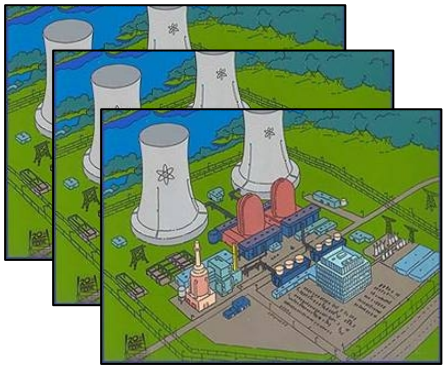


Project 2: the real problem

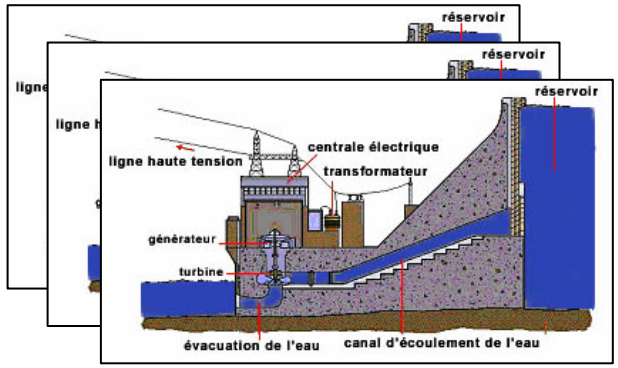
“N-dimensional stochastic optimization and simulation: application to electricity asset management”

6 – Second Motivations and Objectives

« Management of French electricity production to control cost while satisfying demand »

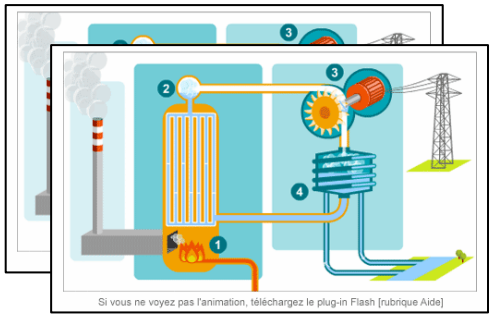


Nuclear energy



Hydraulic energy

Energy trading



Thermal energy

Etc…

Goal: save energetic resources and money

Main levers: the commands to manage the different energetic stocks

→ A N-dimensional stochastic optimization problem!

→ We extend our 1-D distributed stochastic control algorithm to N-D

7.1 – Dynamic Programming Algorithm

Backward dynamic programming algorithm:

$$\text{for } t \leftarrow (M-1)\Delta t \text{ to } 0$$

$$\text{for } c \in \{\text{admissible stock levels}\}$$

$$\text{for } s \in \{\text{possible price levels}\}$$

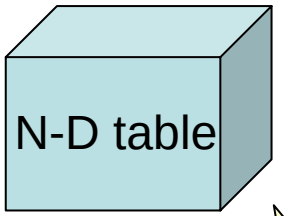
$$\tilde{J}^*(s,c) = \infty$$

$$\text{for } nc \in \{\text{possible commands for stocks}\}$$

$$\tilde{J}^*(s,c) = \min\left(\tilde{J}^*(s,c),\ \phi(nc) + \mathbb{E}\left(J^*(s^*, c+nc) \middle| s\right) \right);$$

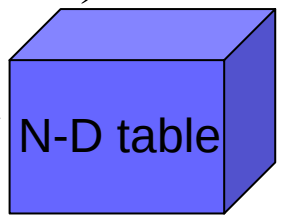
$$J^* \leftarrow \tilde{J}^*;$$

Same kind of algorithm (compared to 1-D gas storage valuation)



Cost [stock levels, prices, commands]

J* at t_n



Cost [stock levels, prices, commands]

J* at t_{n+1}

7.1 – Dynamic Programming Algorithm

Backward dynamic programming algorithm:

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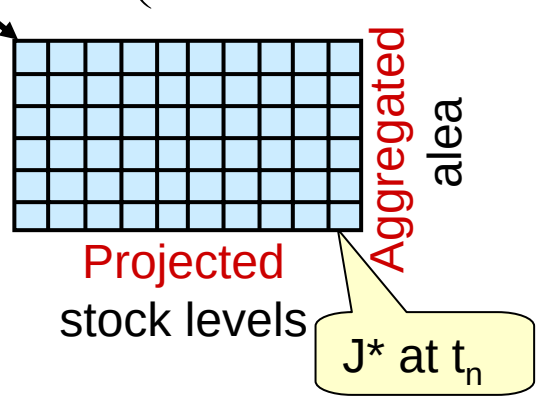
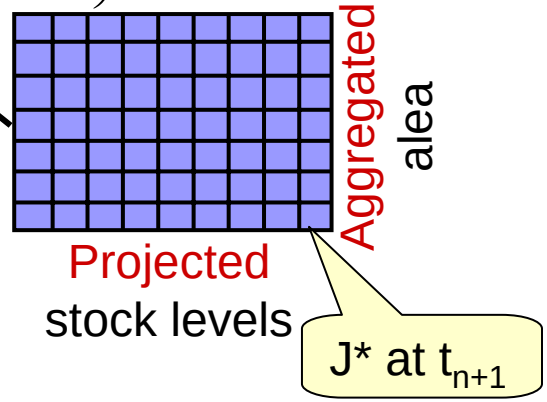
Same kind of algorithm (compared to 1-D gas storage valuation)

2D tables!! (implementation & mathematic optim)





7.2 – Application overview

Part-1: Input file reading and initializations

- Read files and load data in each process memory space
- BG/L PFS → concurrent read (no pb!)
- PC cluster NFS → crash!

→ P0 reads data files and broadcasst data.

Part-2: stochastic optimization

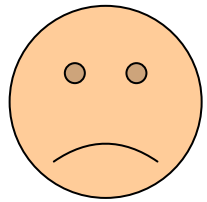
- N-D version of the previous algorithm
- + intermediate results storage

→ Many IO & many communications & huge computations

Part-3: stochastic simulation (compute risk associated to the optimized strategy)

- Independent Monte-Carlo forward simulations
- BUT: requires to read intermediate result of part 2

→ Many IO & many communications & few computations !



8.1 – N-D data distribution strategy

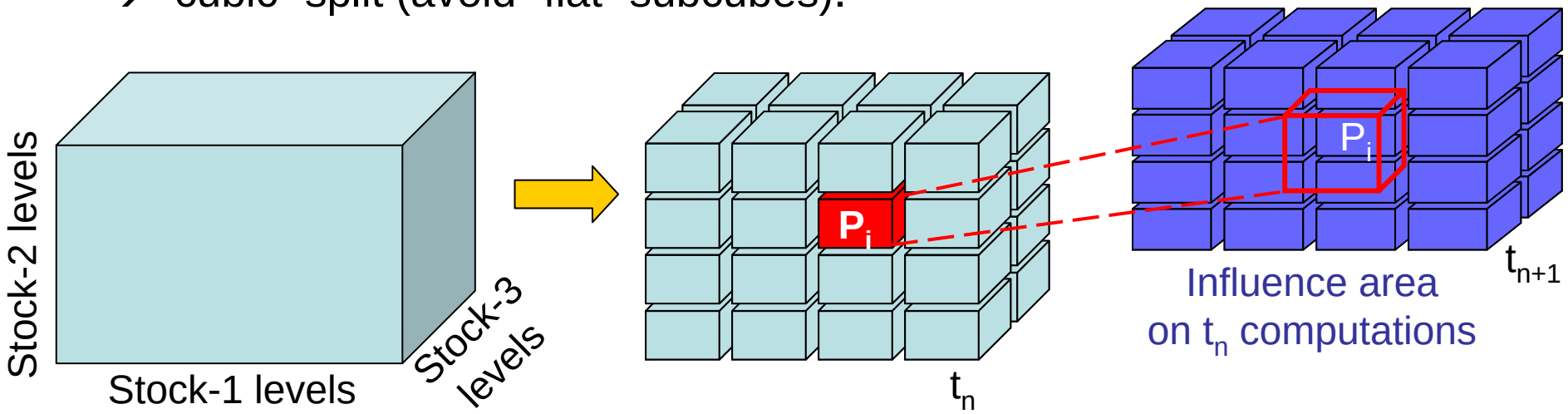
Part-2 data distribution requirements:

- We have to split a N-stock hypercube of profits
- We have NbNodes = 2^k on Blue Gene/L (no constraint on PC-cluster)

Split and map a N-cube of data on a 2^k-cube of computing nodes

Objectives of the split:

- to load balance the data and the computations
- to minimize the communications of the « N-D influence area » !
  → "cubic" split (avoid "flat" subcubes).



8.1 – N-D data distribution strategy

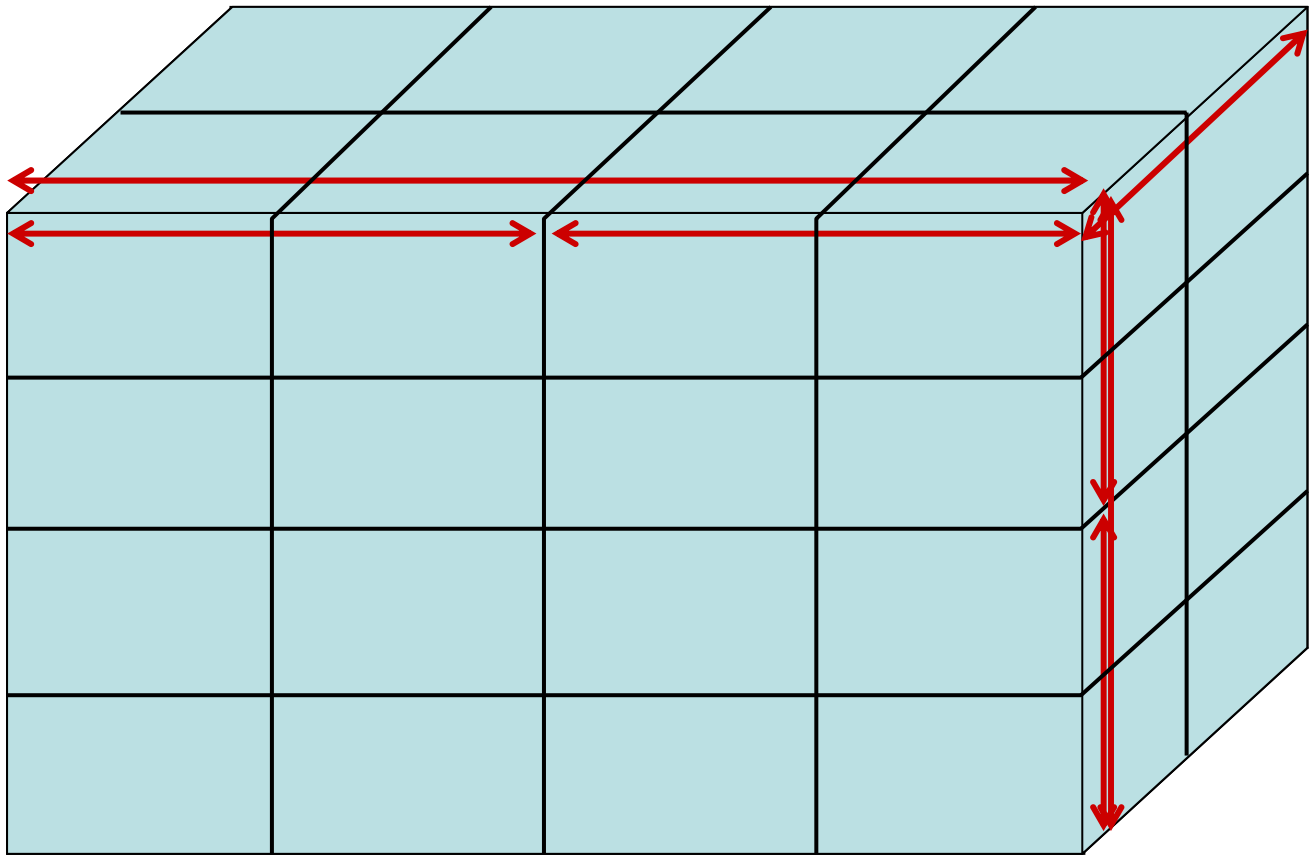
Considering a 3-stock problem:

P_i: Compute the N-dimensional cube split in $P = 2^k$ subcubes, avoiding « flat cubes »

- identify the dimension with the largest « subcube edges »
- split each of these subcube edges

repeat…

Each (MPI) process computes this data distribution **map**

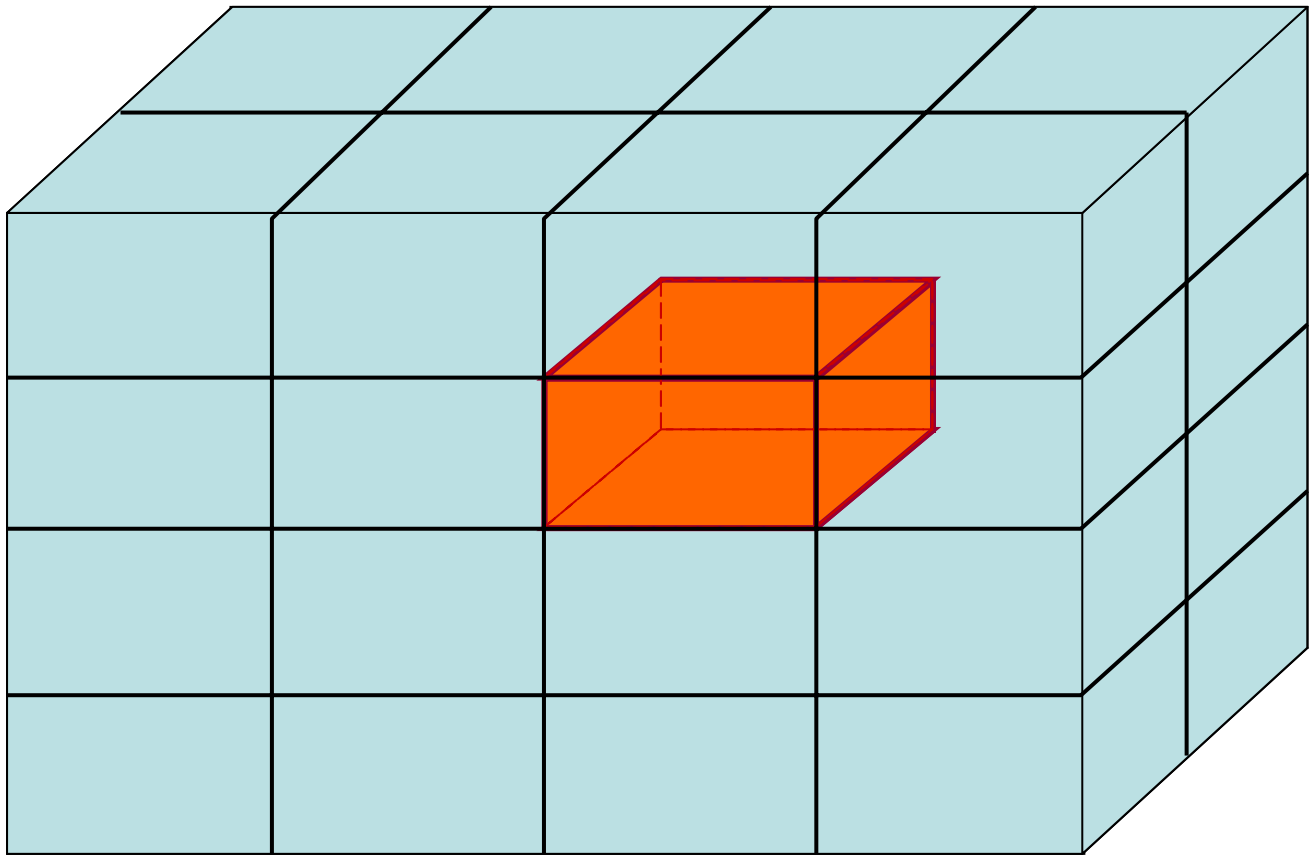


8.1 – N-D data distribution strategy

Considering a 3-stock problem:

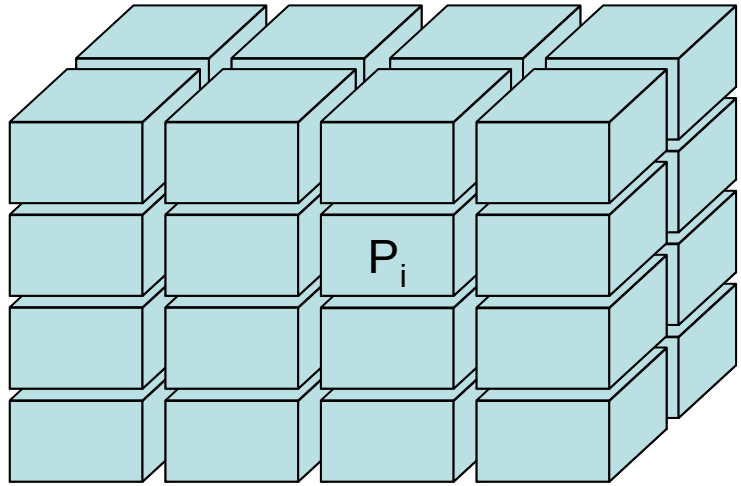
P_i: Compute the N-dimensional cube split in $P = 2^k$ subcubes, avoiding « flat cubes »

- identify its ND-subcube in the global distribution map
- allocate optimal in size datastructures



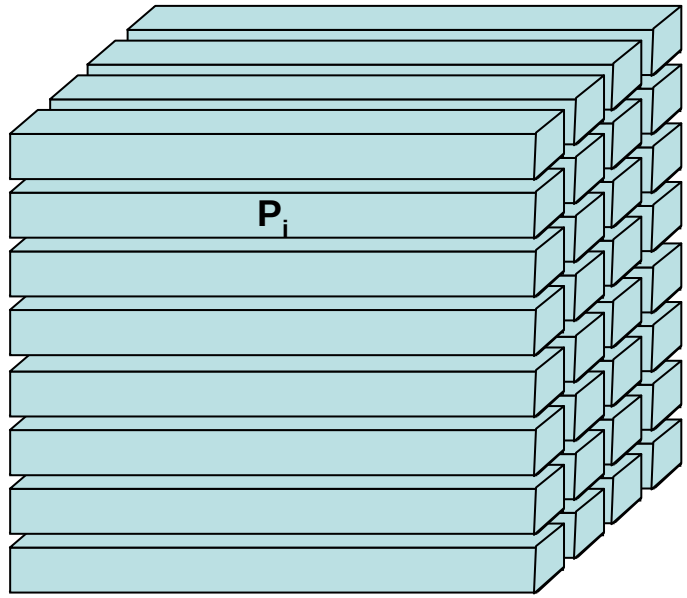
8.1 – N-D data distribution strategy

- When all dimensions can be split each processor manages very “cubic” ND-subcubes:



- When at least one dimensions cannot be split processors manage more “flat” ND-subcubes:

Some stocks are aggregated into one large stock, leading to optimized but complex computations. Then this dimension cannot be split, and parallelization is not optimal.



8.2 – N-D communication scheme

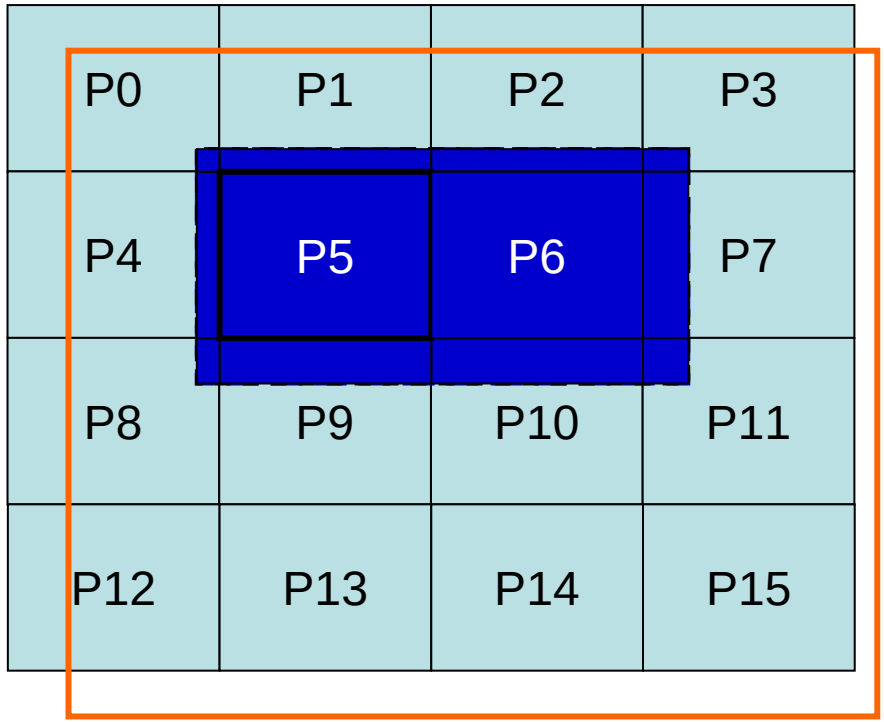
Considering a 2-stock problem:

What happens on **P5** (for example) ?

At t_n, it manages a new 2D-subcube, in the new 2D-cube

… influenced by a 2D-subcube of t_{n+1} data

So it has to establish its routing plan:



P5 Routing plan:

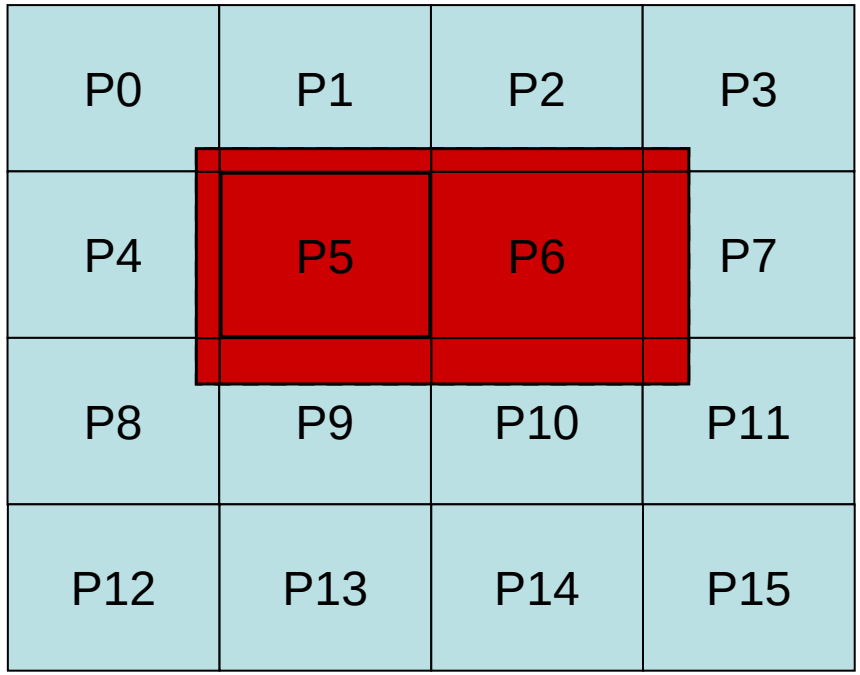
Proc	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Recv																
Send																

8.2 – N-D communication scheme

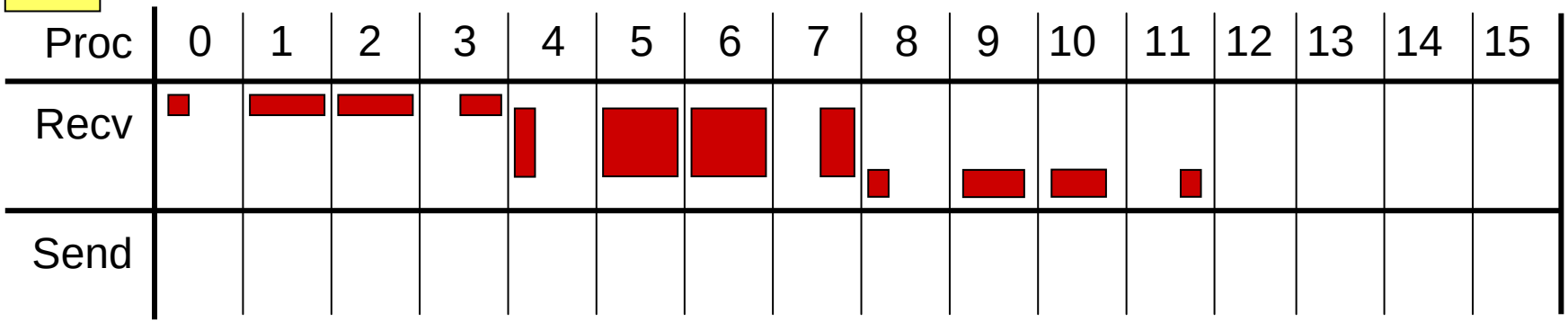
Considering a 2-stock problem:

What happens on **P5** (for example) ?

It determines all 2D-subcubes it has to receive from other processors



P5 Routing plan:



8.2 – N-D communication scheme

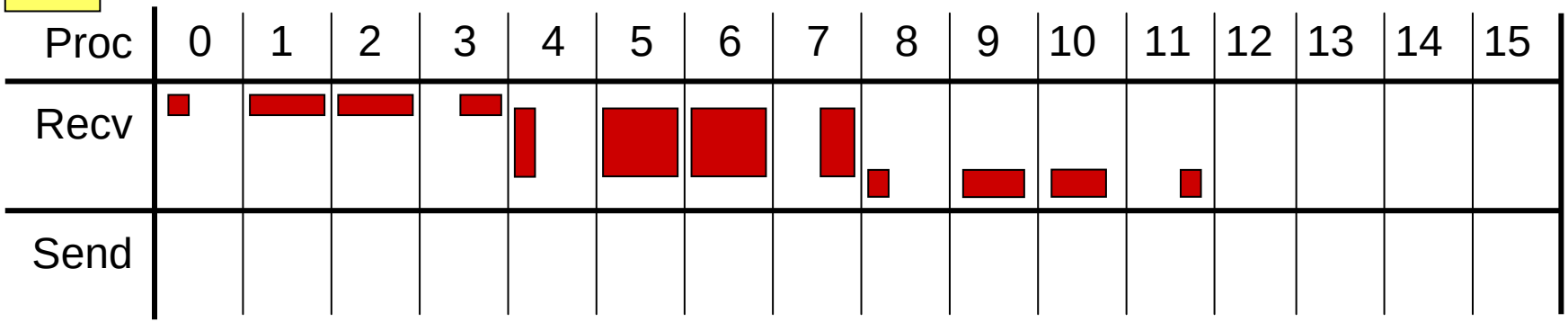
Considering a 2-stock problem:

What happens on **P5** (for example) ?

It determines all 2D-subcubes it has to receive from other processors

P0	P1	P2	P3
P4	P5	P6	P7
P8	P9	P10	P11
P12	P13	P14	P15

P5 Routing plan:



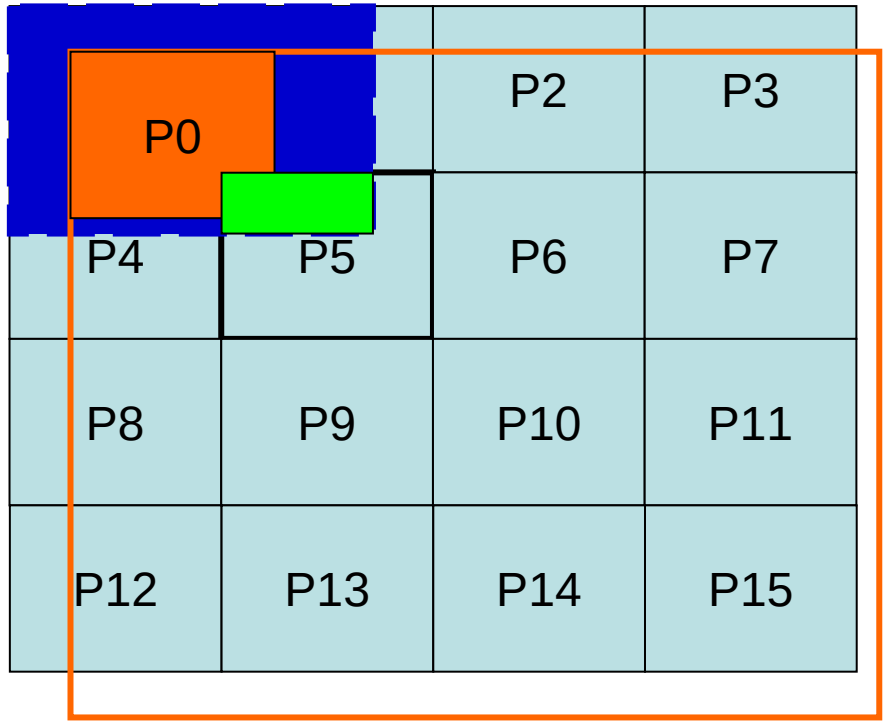
8.2 – N-D communication scheme

Considering a 2-stock problem:

What happens on **P5** (for example) ?

It determines all 2D-subcubes it has to send to other processors:

- compute « influence area » of P0
- compute the intersection with its t_{n+1} 2D-subcube of data



P5 Routing plan:

Proc	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Recv																
Send																

8.2 – N-D communication scheme

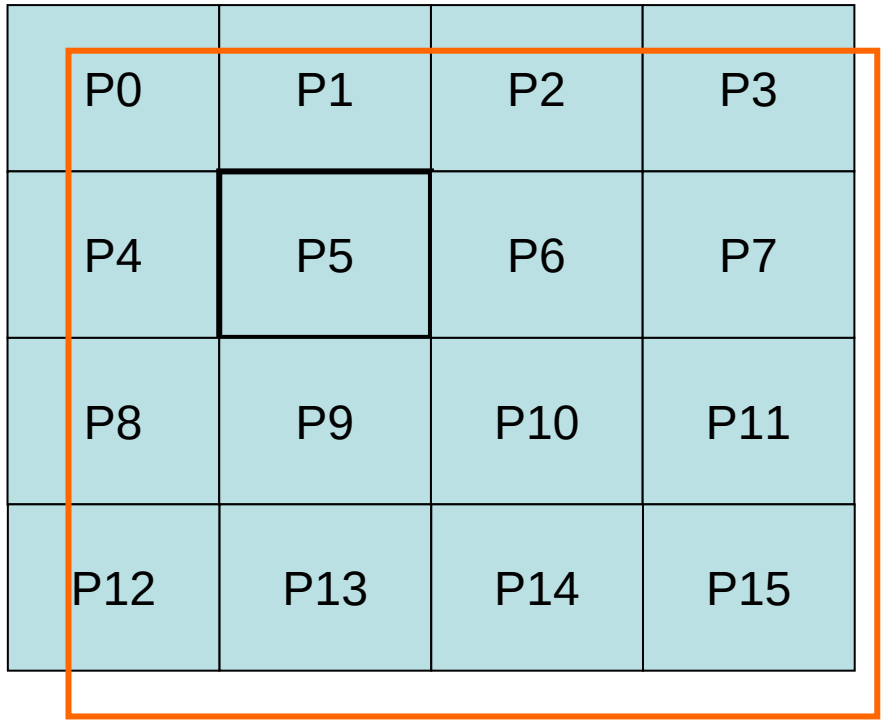
Considering a 2-stock problem:

What happens on **P5** (for example) ?

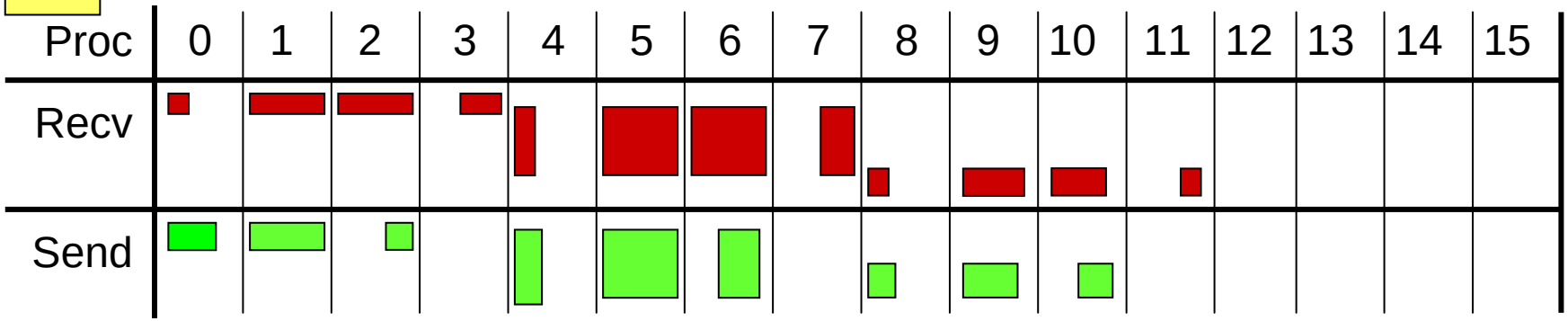
It determines all 2D-subcubes it has to send to other processors:

- repeat with other processors…

The routing plan of P5 is complete!
→ Execute it quickly!



P5 Routing plan:



8.3 – C++ implementation

Parallelization:

- MPI: Mpich-1, OpenMPI, IBM MPI
  communication routines: MPI_Issend, MPI_Irecv, MPI_Wait

  → overlap all communications when executing a routing plan (to speedup)
  → do not use “extra communication buffers” (to size up)

- + multithreading: Intel TBB or OpenMP

  → to speedup and to size up more (than using only message passing)

Scientific computing libraries:

Blitz++, Boost, Clapack, Sprng.

Total:

- 57000 lines of C++ code
- 10% for parallelization management

- Same source code on PC-cluster and Blue Gene/L

Experimental performances

9.1 – Perf. of the optimization part

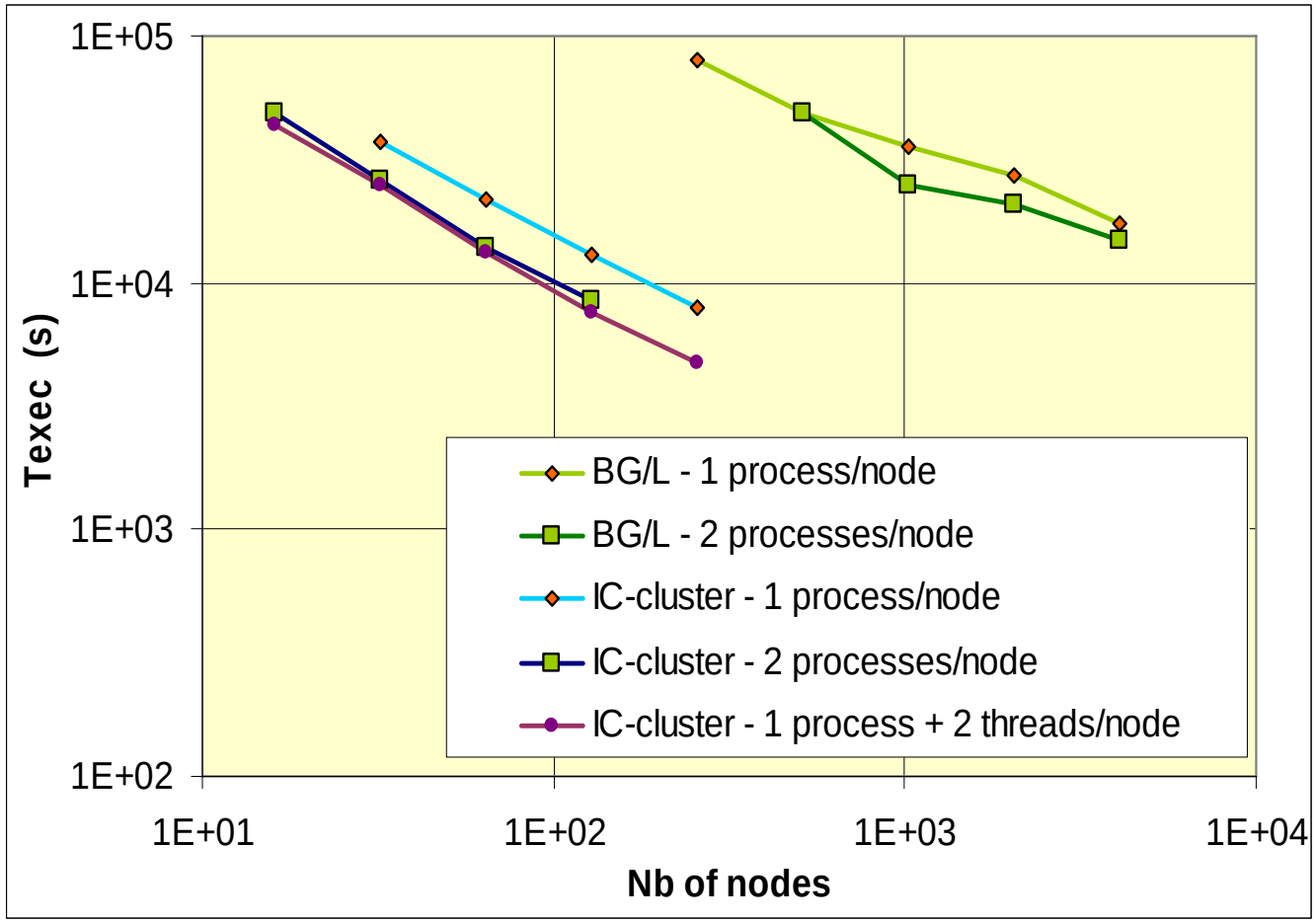
Performances of optimization part of a "7-stocks / 10-state-vars" computation
Using: MPICH-1 and TBB on IC-cluster (a PC cluster), IBM MPI on BG/L

- Similar curves (compared to 1-D gas storage valuation)

- Performance on BG/L:
  - less important …
  - high fluctuations …

Strange! We investigate.

- MPICH-1 on IC-cluster:
  - 1 MPI process + 2 threads: not better than 2 MPI processes,
  - many failures beyond 64 nodes.

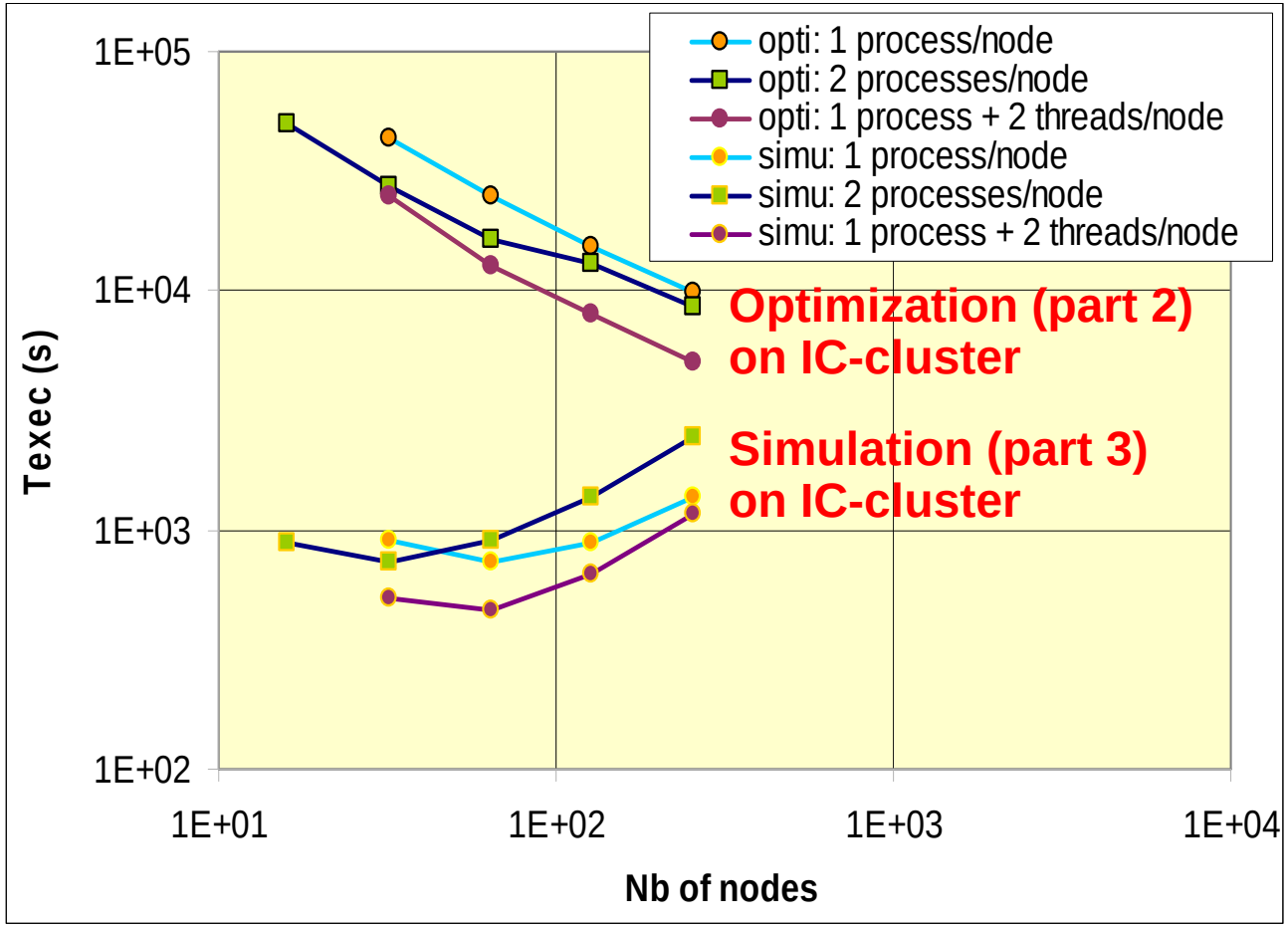


Experimental performances

9.2 – Perf. of optim. & simu. parts

Details of the performances of a "7-stocks / 10-state-vars" computation
Using: OpenMPI and OpenMP on IC-cluster (a PC-cluster)

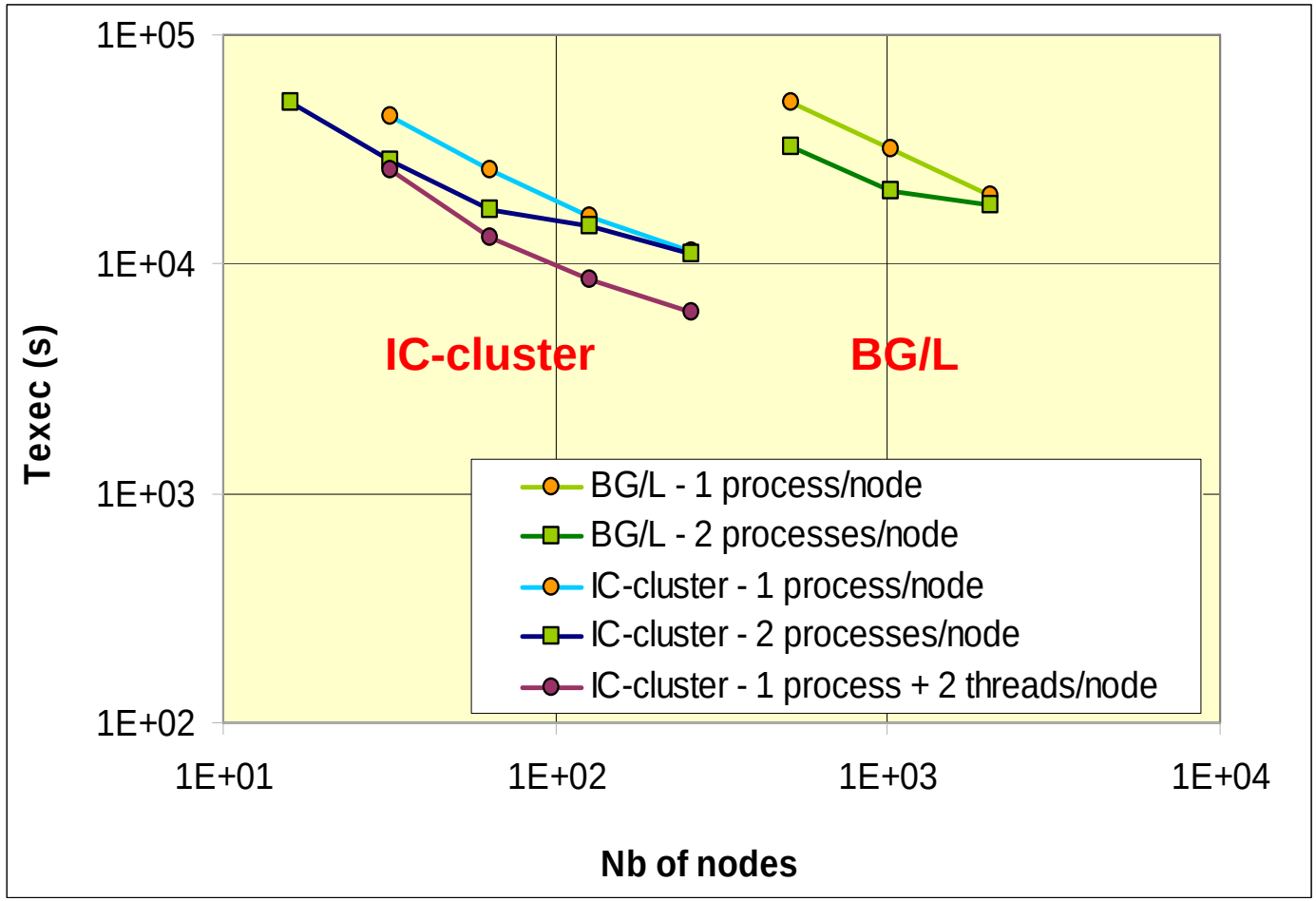
- OpenMPI on IC-cluster:
  - no failure beyond 64 nodes
  - slower than MPICH-1 (approx. +20%)
  - 1 MPI process + 2 threads: better than 2 MPI processes,
- Optimization: scales
  Simulation: does not scale!
- Best implementation:
  1 process + 2 threads,
  (both for opti & simu)



9.2 – Complete computation perf.

Performances of a "7-stocks / 10-state-vars" entire computation (parts 1, 2 and 3): Using: OpenMPI and OpenMP on IC-cluster (a PC cluster), IBM MPI on BG/L

- Part 3 (simulation) limits the speedup
- 1 MPI process + 2 threads/node: best implementation
- Threads not available on BG/L,
- OpenMP threads on IC cluster
- Performance measurement on BG/L in progress…



Conclusion and perspectives:

10.1 - Conclusion

From parallel computing point of view:

Complex parallelization (with many comms. and IOs)
Speedup, size up and scalability on PC-cluster and BG/L supercomputers

More experimentations are required on BG/L
New experimentations are required on PC-cluster with different MPI libraries

Improvement of the stochastic simulation distributed algorithm is required…

From a user point of view:

Usual limit is 4-5 state variables on sequential machines!

Our software :

- ✓ currently allows to process a « 7-stock/10-state-vars » problem in less than 2h on our PC-cluster.
- ✓ supports different theoretical models and allows to quickly experiment and evaluate new models

10.2 - Perspectives

Next steps:

- More experiments on BG/L – 8192 processors (using IBM MPI)
- Experiments on BG/P - 32000 processors (using IBM MPI + OpenMP)
- Serial optimizations on BG, with the help of IBM
- Improvement of the stochastic simulations (part-3)

May-June 2008

Exploitation for energy management:

- Quick implementation and large scale evaluation of new models
- Design and experimentation of new and larger use cases

→ Towards a global optimization of EDF energy production.

May-December 2008

Multi-site Grid experiments:

- Multi-site experiment on Grid'5000
- Impact of WAN on performances ?

  collaboration with AlGorille/INRIA team (Nancy)
- Improvement of process mapping on a multi-site Grid ?

  collaboration with Reso/INRIA team (Lyon)

June 2008 …

Stochastic control optimization & simulation applied to energy management: From 1-D to N-D problem distributions, on clusters, supercomputers and Grids.

Questions ?