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IMPROVING THE USE OF RESERVOIR SIMULATION THROUGH PARALLEL COMPUTING AND OPTIMIZATION TECHNIQUES

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Abstract. *Reservoir simulation is a valuable tool for reservoir engineering and management. Most of the applications require many simulation runs either because there are uncertainties in reservoir characterization and the model has to be calibrated or because many options have to be tested in manual or in optimization procedures. In the past, computer time was one of the most limiting variables but nowadays computers are becoming less expensive. On the other side, human resources are becoming more valuable so people must have tools to make the best use of their time. Despite of these facts, many important decisions in reservoir engineering are still strongly based on manual procedures even when computers, parallel algorithms and automation tools are available. Furthermore, many companies do not use their network adequately. In order to contribute to a change in this scenario, this work shows (1) some advantages of building tools using reservoir simulation, parallel computing and optimizing techniques to history matching and reservoir management decisions, and (2) how to make the best use of existing networks and PVM (parallel virtual machine) to accelerate such processes. A case study using an offshore field is presented to illustrate (1) the advantages of having a computer program to automate some steps of production history matching and (2) the time savings obtained by parallel computing.*

Key-words: *Simulation, Reservoir, Optimization, Parallel Computing*
Palavras-chave: *Simulação, Reservatórios, Otimização, Computação Paralela*

1 INTRODUCTION

The main objective of this work is to present some ideas to improve the efficiency of the use of reservoir numerical simulation, specially in processes of production history matching, reservoir management and use of optimization routines to improve reservoir performance.

Most of the applications of reservoir simulation are related to uncertainty. In reservoir characterization, production history matching is used to adjust a proposed model until simulation results match observed data. In the area of reservoir development, the impact of uncertainties in the final value of the reservoir can be evaluated through several runs. In reservoir management, several alternatives can be tested using simulators. These are only a few examples; reservoir engineers are using reservoir simulators for several purposes and most of them require many runs.

This tool is becoming more useful due to the improvements in computer hardware and software. The speed and capacity of computers and the advances in commercial simulators allow the use of more complex models, which can give more confidence to the results. However, these improvements in the computer area are very fast and, many times, users don’t know how to make the best use of available resources.

The most evident examples are:

- the lack of knowledge of the capacity of use a network of workstations as a virtual parallel machine, which can be easily done using software like PVM and MPI,
- the non use of the network during long periods of time (*e.g.* nights and weekends);
- the misuse of reservoir simulation options, which yield very long simulation runs,
- the non use of optimization techniques to take important decisions, which may have a great impact in the value of the projects, etc.

In this paper, we try to show very simple procedures that can help us to make a more efficient use of simulation. These procedures can be obtained from the automation of several steps of our tasks and use parallel computing and optimization techniques to accelerate some the created procedures.

2 RESERVOIR SIMULATION

Reservoir numerical simulation (Aziz and Settari (1979) and Mattax *et al.(1987)*) has become an important tool to several research and practical activities in the petroleum industry. There are several limitations and many errors involved in the process of reservoir modeling using available numerical simulators. However, they are still the most viable and reliable way to predict production performance and to understand reservoir flow mechanisms.

To make the best use of such an important tool, constant training is necessary because reservoir simulators are always incorporating new options and because computers are becoming faster and increasing their capacity to accept models that are more complex. However, we can observe that many people don't use simulators adequately, even in very simple tasks. Some of the mistakes can yield incorrect physical answers and these have to be reviewed very carefully.

However, there are common mistakes, which can increase significantly the time of simulations are: use of incorrect numerical options, use incorrect number of layers and blocks, choice of wrong options for output variables, etc. Other common mistakes are: running the simulation in a slow or busy machine, running the simulation when the network is very busy, running to many simulations inadequately (sometimes the same simulation is performed again because output data is not stored), etc. Furthermore, users spend a lot of time preparing the runs and viewing results. Sometimes there are so many results to compare that the most important aspects are not observed.

Some of these problems can be correct by automatic procedures that can save a lot of time from the users, who can concentrate in tasks that are more important. Some of these procedures are discussed here.

3 PARALLEL COMPUTING

The high time consumption of reservoir simulations requires development of codes that take advantage of parallel machines. However, the development of petroleum engineering software is not following the improvement of parallel computer technology. One reason for this gap may be the complexity of the development of parallel reservoir simulators.

There are two possibilities to make use of parallel computing. The first one is to change the simulators codes to send several parts of the program to different processors. We call that internal parallel computing. This procedure has many advantages but (1) the development of such software can be very complex, (2) sometimes we don't have access to codes, and (3) many times there are several simultaneous simulations in the network and there is no advantage in sending part of the tasks to a slave machine that is running another simulation.

The second possibility is to take advantage of parallel computers and a network of workstations without modification of reservoir simulators codes. Several authors (Ouenes *et al.* (1995), Salazar *et al. (1996)*, Machado and Schiozer (1997), etc.) have used external parallel computing to accelerate different procedures that required several simulation runs. By external parallel computing, we mean an efficient distribution of the simulations through the network, where each simulation is performed in a different processor. The most common tool used by these authors is the software PVM (Parallel Virtual Machine).

PVM is a public domain software that allows the development of programs in C, C++ or FORTRAN that that can send "slave" tasks to different machines in a network. In the case of external parallel computing, these slave tasks are simulation runs. A great advantage of PVM is that the network can be composed by machines operating with different operating systems.

In this work, we describe a program called MPS (Module for Parallel Simulations) that uses PVM to distribute the runs efficiently in a network taken into account the speed and dynamic characteristics of each machine. All others modules described in this paper use MPS to run the simulator.

4 MODULE FOR PARALLEL SIMULATIONS - MPS

The program MPS was developed with the objective to manage efficiently a great number of simulations generated by several procedures in reservoir engineering problems. Two characteristics of these simulations are that most of them are independent (so they can be performed in parallel) and that the required time is always much greater than the communications among machines in a normal network (required by PVM).

MPS organizes a queue of processes that are spawned to different execution cells in the machines (hosts), according to the following characteristics:

- relative speed of the host;
- capacity and advantages of the machines to perform more than on simulation at the same type (different execution cells);
- load of each machine;
- permission and/or priorities to users to use simulators in a group of machine at a given time; and
- number of available licenses.

It can be observed in Figure 1 that for a homogeneous network (Network B of Figure 2), the savings are greater but even for heterogeneous networks (Networks A and C), there is still a significant reduction in the total time. It is also possible to affirm that there is an ideal number of workstations to be included in the virtual machine to get the best use from the network but the program can obtain that automatically. Therefore, the users don't have to spend time in these basic tasks and can concentrate on the main aspects of the problem.

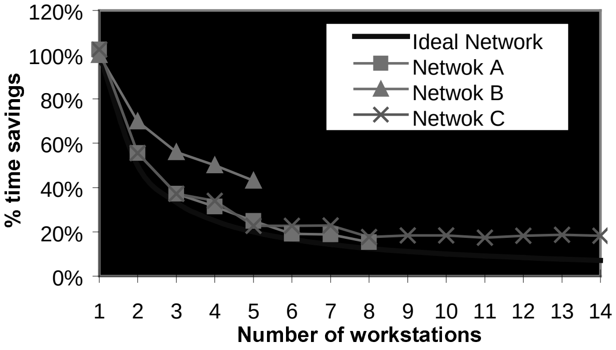

Figure 1 – Time savings using parallel computing compared with the process in the faster host.

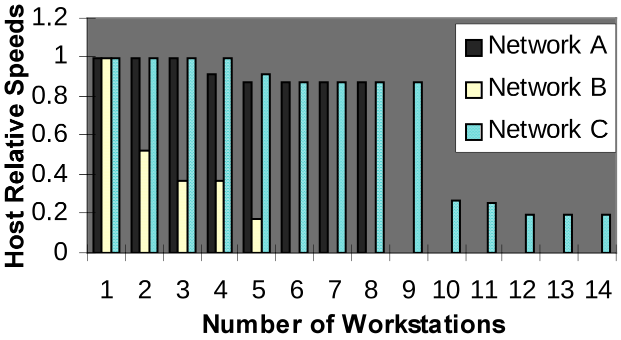

Figure 2 – Relative speed of workstations for three networks

5 OPTIMIZATION TECHNIQUES

Other important tools to be used along with reservoir simulation are optimization techniques. There are many algorithms available and they are applicable to different types of problems. The most common can be represented by a maximization or minimization of an objective-function, which can be net present value of an project, oil production from a field, difference between simulated and observed data in history matching procedures, etc.

However, there are some particular characteristics of the problems related to reservoir simulations that can change the applicability and procedures used in normal optimization procedures:

- there are so many uncertainties and parameters involved in these processes that there multiple acceptable solutions to the problems;
- there evaluation of the objective-function is very time consuming so there must be an important compromise between number of iterations and precision of the results;
- the nonlinearity of the problems can yield so many oscillations in the objective function that many existing methods are not able to find the solution within a reasonable number of iterations.

There are several examples of application of these techniques to a great number of problems. Leitão and Schiozer (1999), for instance, have presented an example of application for a history matching problem, where optimization techniques are used to find the best combination of values for certain parameters of the reservoir to minimize the difference between simulated and observed data for pressure and water production. There are many other works in this area.

Other examples tested in this research were: to find the best completion interval to minimize water conning problems (Kikuchi *et al.* (1997)), to find the best location of a new well to maximize net present value of a project. These problems can be best executed using programs that work with input and output data from a commercial simulator. All runs can be performed using MPS.

Because many of these problems result in very irregular function, methods that use derivatives may have convergence problems. For this reason, Leitão and Schiozer (1999) recommend direct search methods, which are more robust. Another good alternative is to use only discrete values for the parameters. This procedure was used with success in the same type of problem presented in Leitão and Schiozer (1999), and it is recommended for simulations, which require a high computational effort.

The basic idea is to avoid an excessive number of simulations by allowing the parameters to assume only discrete values. Figure 3 shows an example, where two parameters are analyzed to minimize an objective function represented in the third dimension by different colors (darkest color represents the minimum of the function). Most of the optimization techniques require several evaluations of the function in the darkest region, *i.e.* near the minimum. However, many times, the precision needed to the value of the parameters (P1 and P2) is not a critical aspect. Therefore, only points represented by the nodes of the grid can be simulated.

There are three main advantages of this procedure. The first is that the number of simulations, in general, decreases. The second if that users don’t have to choose a tolerance for the objective function, which sometimes is difficult to choose, but a tolerance for the parameters, for which, in general, they have a better feeling. The third advantage is observed when very complex functions are analyzed, where several local minimums can occur. In these cases, one possible alternative is to start different jobs to find different solutions. In such a case, nodes that were simulated in one job don’t have to be simulated again.

This procedure can be used also in more than one step where nodes can be refined near the solutions.

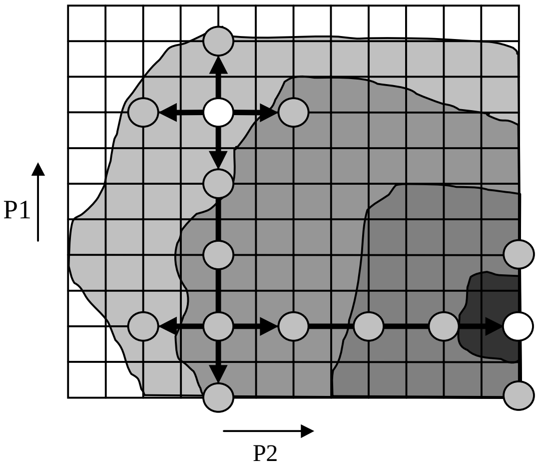

Figure 3 – Example of surface representing an objective function and an optimization procedure using two parameters.

6 APPLICATIONS

The number of applications that can benefits from a combination of reservoir simulation, parallel computing and optimization techniques is very high. A few cases are described next and an example is presented

6.1 Automated History Matching

A completely automatic history matching is not a viable objective due to the high complexity of the problem and to the number of variables involved. However, the automation of some steps is not only possible but also very useful. The degree of automation depends on the physical aspects of the reservoir, the stage of the problem, the available computer resources and the quality of the available tools.

Two important tasks of the process are (1) choice of the parameters to include in the matching, and (2) calculation of the best combination of the parameters to minimize the difference between simulated and observed data. The first was studied by Machado and Schiozer (1997) and a similar procedure is used in the example presented in this paper. The second was studied by several authors (Ouenes *et al.* (1995), Salazar *et al.* (1996) and, Leitão and Schiozer (1999)). A procedure that uses only discrete values of the parameters was developed and included in the next example.

6.2 Example

An example of history matching using the techniques described in this paper is presented here. A computer program was developed using a graphic interface in order to help in the interpretation of the results.

It was performed a history matching of the water production of a real field containing 48 wells. The process was divided in steps. The initial model was obtained through reservoir characterization, and after some modifications, it resulted in the water production presented in Figure 4 (base model). At this point, the software was used in alternate steps composed by sensitivity analysis (program ASAHP) and optimization procedure (program MOT).

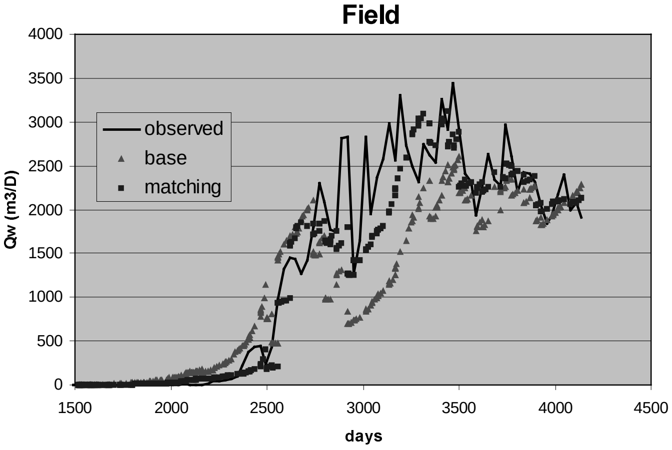

Figure 4 – Results from field history matching using procedure described in the paper

An example of the results obtained by ASAHP is shown in Figure 5. Graphic bars are used to show three important information:

- An index of sensitivity analysis of the parameters to indicate the importance of each parameter in the process,
- An index informing the relative distance between simulation and observed data,
- Colors indicating the correct direction to change parameters (red – wrong direction, blue – correct direction but modification should be greater, green – correct direction but modification should be smaller).

This type of information helps users in the choice of parameters and allows a reduction of time in post-processing results from simulations. It also helps in the understanding of physical aspects of parameters modifications. A parameter here can be any variable that can be modified in the simulation, for instance, relative permeability, porosity in the entire reservoir, permeability in a defined region, etc.

After choosing the parameters with greatest importance in the process, the program MOT is used to find the best combination of values for these parameters (using the optimization procedure described here). Table 1 shows the results from alternate analysis of ASAHP and MOT. Initially, four parameters were used and two were selected. An optimization of these parameters were then performed followed by similar analysis using these parameters by layers. The last step used vertical permeability by layers but it can be observed that, as the procedure goes, the efficiency is smaller. The reduction of the objective function is smaller and the number of simulation increases. The matching is presented in Figure 5.

At this point, the same analysis is used for each well. The matching of the well with the poorest initial result is presented in Figure 6. After a few steps, the process was stopped presenting the final result in Figure 7. Depending on the objectives of the study, the process can be stopped at different stages.

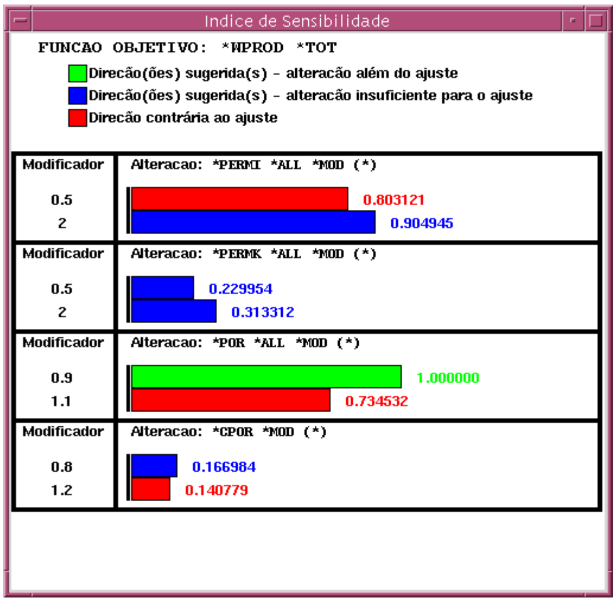

Figure 5 – Example of sensitivity analysis of 4 parameters in the water history matching

Table 1 – Steps from automatic history matching

Analysis	**Type**	**Property**	**Simulations**	**Results**	**Base Model**
1	ASAHP	kh, kv, cr, ϕ	9	kx e ϕ	base0.dat
2	MOT	kh, ϕ	20	Great reduction of FO	base0.dat

3	ASAHP	Kh por camadas	7	Kx3 e kx4	base1.dat
4	MOT	kh3, kh4	24	Great reduction of FO	base1.dat
5	ASAHP	ϕ por camadas	7	ϕ3 e ϕ4	base2.dat
6	MOT	ϕ3 e ϕ4	30	Small reduction of FO	base2.dat
7	ASAHP	Kv	7	kv12, kv3, kv4	base3.dat
8	MOT	kv12, kv3, kv4	45	Very small reduction of FO	base3.dat

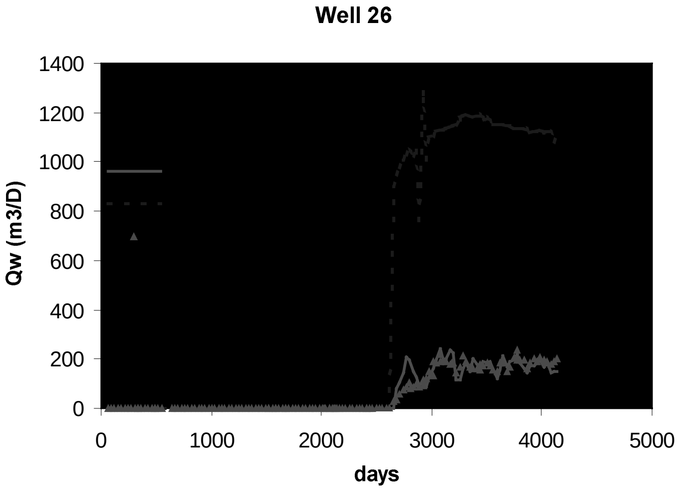

Figure 6 – Results from well history matching using procedure described in the paper

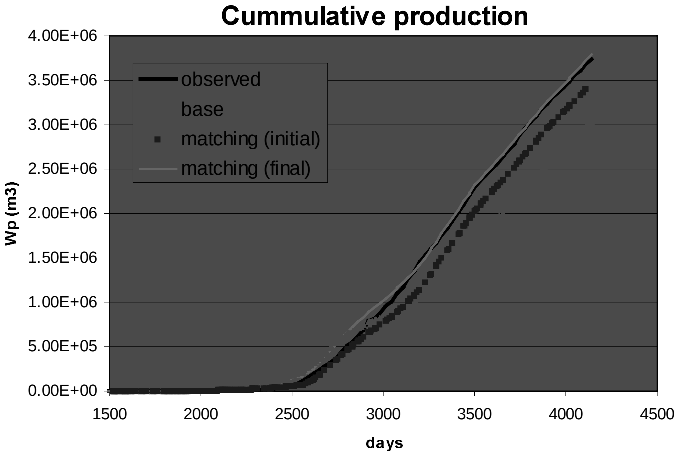

Figure 7 - Results from history matching using procedure described in the paper

In this example, each simulation was taking approximately 20 minutes. Using a network of 8 workstations, the whole process took less than 3 days. From the user, it is required only, the initial model, the choice of the parameters and their acceptable limits and the decision of the point to stop the process. A similar procedure can be used at different stages of the process with different objectives.

6.3 Other Applications

Several other applications can benefit from simulation integrated with parallel computing and optimization techniques. An example is the work from Andrade Filho

(1997). We have been working, with a few other examples. Kikuchi *et al.* (1997) developed a procedure to find the best completion interval to avoid water conning problems. The study of the impact of uncertainties in reservoir development is another useful and important application. The choice of the best location and characteristics for wells can have several automatic steps. The decision of the optimal number of wells and the choice of the best location of a well to maximize the net present value.

For instance, for the same field presented in the history matching example, there was one well with a poor financial return (well 43). An automatic procedure can be used to investigate regions of the reservoir with good possibility of a new well (based on saturations, permeability, etc.) and using simulation, a routine can be used to optimize the location of this well. Table 2 shows the results after these two steps, for several potential locations, including well 43. The best solution (best net present value) was obtained for the location 24x10 (layers 1,2,3,4).

The same procedure was used for two wells finding two locations (24x10 and 19x11) (see Table 3) but the net present value per well was significantly reduced. Therefore, based on simulation results, the user has a better tool than the usual inefficient trial and error procedure.

These are just a few examples. Many others can be developed and with the increasing capacity of computers and parallel techniques, they are becoming viable and necessary, especially because companies have less time to decide. Human resources must concentrate on the main aspects of the problems.

Table 2 – Results from optimization of net present value of a new well

Layers			**1,2,3,4**	**3,4**	**1,2**	**1,2,3,4**
Well	**All with 43**	**All without 43**	**Position 24-10**	**Position 26-03**	**Position 19-11**	**Position 22-07**
Np (MM m3)	35.58	35.34	35.01	35.55	35.13	34.60
Gp (MM m3)	4831	4982	5304	5224	4936	5259
$ (MM US$)	911.62	910.12	990.29	958.38	967.08	974.64
NPV (MM US$)	906.32	910.12	**984.99**	953.08	961.78	969.34

Table 3 - Results from optimization of net present value of two additional wells

Well positions	**24x10, 22x07**	**24x10, 19x11**	**24x10, 26x03**	**26x03, 19x11**	**26x03, 22x07**	**19x11, 22x07**
VPL (MM US$)	1004.05	1008.01	1007.98	998.46	1003.05	1002.17
VPL (MM US$) (per well)	502.02	**504.00**	503.99	499.23	501.52	501.08

7 CONCLUSIONS

The research developed in this work allowed the following conclusions:

- Today, with the potential and price of computers, it is very important to develop tools to improve the quality of decisions in the petroleum industry.
- The integration of characterization, simulation, parallel computing and optimization techniques can result in the development tools that can contribute to accelerate several tasks. Many times, simple procedures work better than complex programs that tend to be difficult to use.
- History matching and reservoir development can benefit from automation tools. Complete automatic solutions are not viable but several steps of the process can be automated.
- The cases presented here are just a few examples of how the automation of the process

can improve the quality of the decision-making processes.

- Parallel computing can reduce the cost of hardware because existing networks can be used as a virtual parallel machine, even during the nights and weekends when many networks are not fully used.

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