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Introduction

The main objective of this thesis is to find effective solutions for collaboration of team workers during the execution of Large Scale Engineering Projects (LSEP). The research is based on actual operational needs of Petrobras, a large Brazilian governmental oil & gas company. For this thesis we have focused on Offshore Engineering Projects as our case studies.

We have developed a prototype of the proposed architecture, called CEE (Collaborative Engineering Environment), considering requirements such as collaboration, workflow coordination, and visualization. CEE allows team workers to concentrate in the task of solving a problem using all the resources available, from the execution of large engineering simulations on a Grid to the collaborative visualization of results in an immersive or desktop environment.

1.1.Motivation: Large Scale Engineering Projects (LSEP)

Contemporary Science and Engineering projects, specially the large scale ones, have the following common characteristics:

- They are highly data intensive and computational demanding.
- They are highly multidisciplinary, requiring the cooperation of different specialists.
- They often involve large distributed teams of researchers working together on a single complex problem.
- Each team of specialists has its own model of the engineering artifacts to be designed, simulated or analyzed, and may use several different models or partial models for different purposes during the project life cycle.
- Specialists have limited ability to understand each other's models. They communicate using a shared vocabulary, but not necessarily shared technical knowledge [BR92].

- They proceed by successive refinement of the models, which are coordinated and updated together. Design decisions are negotiated by specialists among themselves [BR92].

Due to their huge complexity, LSEP are divided into smaller interrelated subprojects where each one has a complementary representation of the models. Figure 1.1 schematizes an aircraft project, and many of its distinct subprojects, that might be executed by different teams of specialists. Any system to support LSEP must stress a *coupling solution* to these diverse simulations and models.

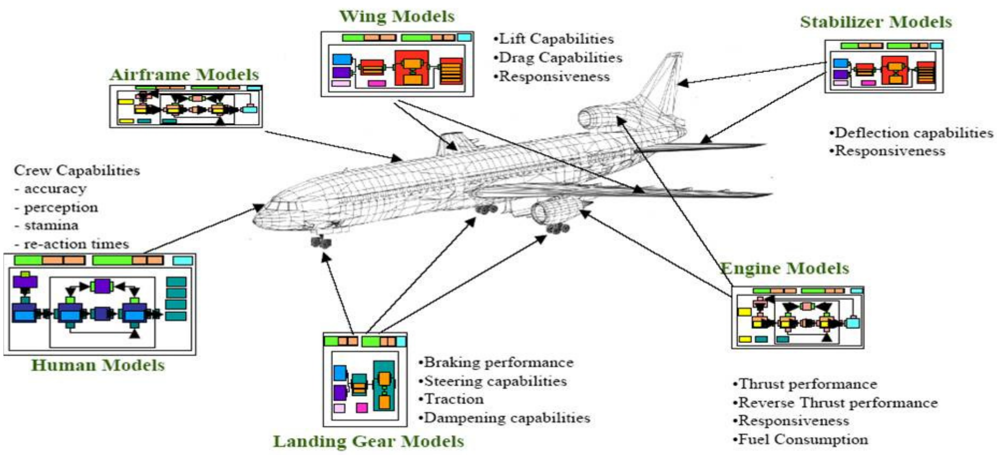

Figure 1.1: Collaboration of different simulations in an aircraft project.

LSEP also involve the interaction of people where information and data are distributed and knowledge is shared at request. Moreover, LSEP demand lengthy and complex processes involving multidisciplinary teams, usually geographically distributed with multiple information and storage systems and also using distributed and heterogeneous resources. Therefore, an integrated computer-supported solution to LSEP must include *support for human collaboration* and *distributed resource management*.

Finally, LSEP have a very dynamic nature, i.e., they cannot be completely planned in advance and are under change during their execution. For these reason, *adaptability* is also an essential issue.

1.1.1. The Role of Visualization, Remote Collaboration and High Performance Computing

The Oil & Gas industry has seen increasing costs of finding and extracting hydrocarbons, especially in remote locations, ultra-deep water reservoirs (400 m or deeper) or in hostile environments. The development of deep-water oil & gas reserves constantly faces the challenge of reducing costs of its components and activities in the selected exploitation scheme. Therefore, High Performance Computing (HPC), Visualization and Remote Collaboration technologies are being heavily used to improve productivity, leading to better cost-performance ratios.

Earth Sciences and Engineering are challenged to manage and interpret increasing amounts of data coming from the field or generated by computer simulations. The typical work of scientists and engineers consists in first detecting features, then measuring them, and finally generating a model that supposedly tries to explain those observed features. This visual approach to science and engineering is powerful, as the human brain excels at visually identifying patterns. As Edward Tufte [Tufte83] wrote more than two decades ago: "At their best, graphics are instruments for reasoning about quantitative information. Often the most effective way to describe, explore and summarize a set of numbers – even a very large set – is to look at pictures of those numbers".

Figure 1.2: Engineers in a collaborative section in oil & gas.

Visualization and Remote Collaboration technologies help us to bridge the cost-productivity problem. High-end visualization systems are commonplace in the oil & gas industry, especially in the Exploration & Production (E&P) segment, also called Upstream. In former times, the aerospace and automobile industries have shown sensitive gains in efficiency and effectiveness when carrying out Enterprise projects using Virtual Reality technologies. In the nineties oil companies were among the first to make industrial use of the so-called virtual reality centers (VRCs), equipped with immersive projection systems with large display walls (e.g., cave, cave-like, curved-panel, and powerwall), videoconference tools, among other equipments. Techniques such as three-dimensional geometric modeling, scientific visualization, immersive virtual environments (VEs), commonly used in VRCs, pushed the limits of teamwork activities in Geosciences and Petroleum Engineering, especially in Reservoir and Offshore Engineering.

The configuration of VRCs greatly improved visual communication and group collaboration in technical work sessions and decision-making meetings. The possibility of visualizing and manipulating virtual models in the VRCs has completely changed the way of working, notably for geologists and engineers (Figure 1.2 and Figure 1.3).

Collaboration is an inherent demand of Offshore Engineering projects, which require multidisciplinary teamwork, with a high degree of integration among different disciplines. The possibility to share information among several users; to control the execution of many modeling tools; and collaborative visualize and manipulate virtual 3D models in immersive Virtual Environment (VE) are interesting features that add great value to Petroleum Engineering projects.

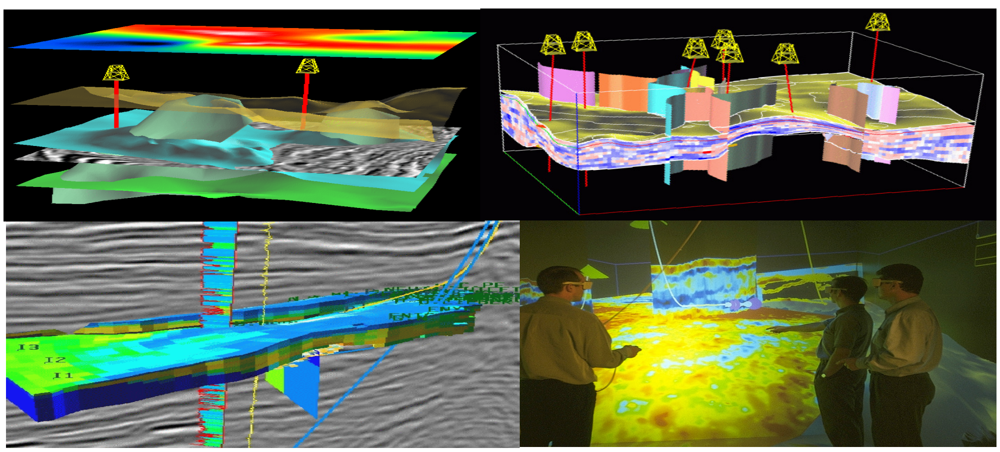

Figure 1.3: Geologists, Geophysicists in a collaborative section

To summarize we notice that VR visualization technologies enhance the content knowledge within any engineering design activity. Used in conjunction with collaboration, VR visualization provides valuable insights for better Decision Support with risk mitigation. Dodd [Dodd 04] has mentioned that the next big management push is the empowerment of interdisciplinary teams with collaboration tools that include remote and immersive visualization on the desktop. Sharing the same opinion as Dodd we emphasize that the combination of Collaborative tools and VR visualization constitutes a powerful component for any software solution for Large Scale Engineering Projects.

High Performance Computing (HPC) has also become vital to oil & gas exploration and production activities due to, among other reasons, the increasingly difficult tasks of locating productive energy supplies and maximizing their extraction. This fact dictates the use of powerful compute resources to handle critical applications, like seismic processing and interpretation, reservoir simulation and offshore engineering simulations.

In the next section we discuss the main characteristics of Offshore Engineering Projects, the main targets of this thesis.

1.2. Offshore Engineering Projects

The research development in Offshore Engineering (OE) projects is conducted to design oil production units, such as platforms, or to adapt old ships to work as Floating Production Storage and Offshore Loading (FPSO) units, for operating in ultra deep water [Moan03].

Floating production systems have been utilized in remote offshore areas without a pipeline infrastructure for many years. However, they have become even more important with the push by the offshore industry into deeper waters. Floating production, storage, and offloading (FPSO/FSO) systems have now become one of the most commercially viable concept for remote or deep-water oilfield developments.

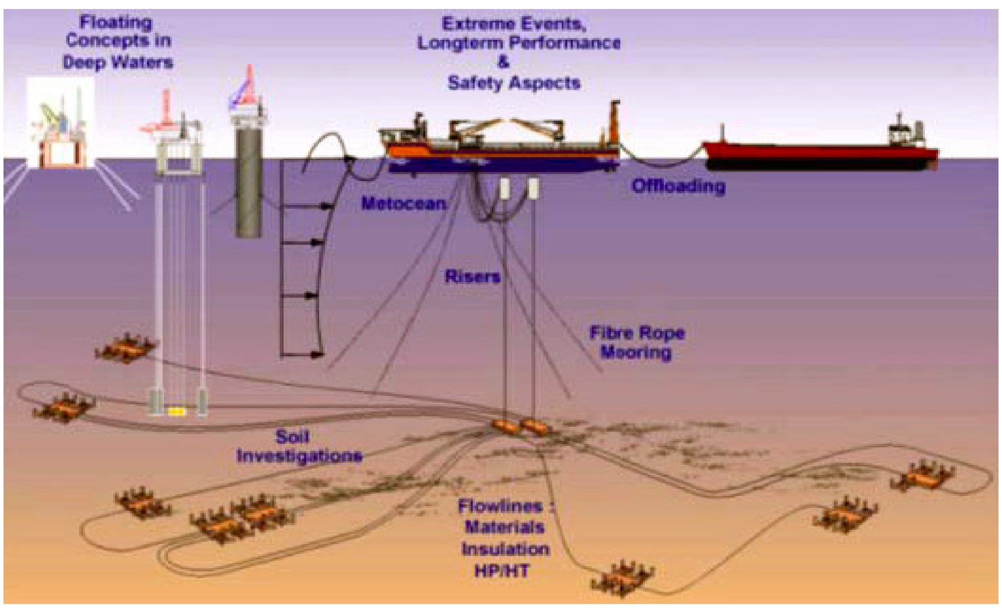

Figure 1.4: Deep-water production system layout.

Deep-water production systems (Figure 1.4), including FPSO/FSO and all the equipments playing a part in the production process, are currently designed by means of complex computational modeling systems. Those systems comprise the areas of structural analysis, meteo-oceanography (related to environmental conditions such as currents, waves and wind forces), hydrodynamics, risers (rigid or flexible steel pipes for carrying oil from the well in subsurface up to the production unit), mooring systems, subsea equipment (manifolds, “christmas-trees”, flowlines, etc), seabed foundations and Geologic/Geotechnical risk assessment.

The project of a new production unit is a lengthy and expensive process; it can last many years and consume hundreds of millions of dollars, depending on the complexity of the unit and how mature is the available technology to make the project technically and economically feasible. Depending on the maturity of the technology, further development should be devised, usually in research centers.

OE projects share all the typical characteristics of LSEP, mentioned above. They have a very dynamic nature, i.e., they cannot be completely planned in advance especially because sometimes the technology has to be developed during the project lifecycle. They involve not only geographically distributed teams but also teams of specialists in different areas using different software tools, both commercial and internally developed. The interoperability of those tools is still an issue in the industry and is a mandatory requisite for any viable collaborative solution [SVR+04].

Finally, due to their huge complexity, OE projects are divided into smaller interrelated subprojects where each one deals with an abstract representation of the others. Because decisions are interdependent collaboration is a key point in this area. Each team activity or new decision can affect other activities. During the conceptual design phase of the project, the work is carried out basically, but not only, by the following teams:

- ***Naval engineers:*** project the hull of the ship, define the optimal positioning of the array of tanks, the mooring system, and study the dynamic stability of the unit based on meteo-oceanographic information about the wind, tide and water currents;
- ***Meteo-Oceanographers:*** provide the current, wave and wind forces profile used during the stability studies;
- ***Structural engineers***: defines the internal structure of the unit and its load capacity;
- ***Production and equipment engineers:*** project the production system, encompassing risers and flow-lines, and plan the installation of deep-water production equipments, such as manifolds and “christmas trees”;
- ***Chemical and process engineers:*** project the process plant based on the characteristics and expected volume of oil and gas that will be produced;

- **_Geotechnical engineers:_** determine the position for anchoring the production unit based on studies of the behavior of the soil-structure interaction.

It can be seen by each team's duties that the need for collaboration is crucial once decisions are very interdependent. Each team activity or new decision can affect other activities. For example, during the design of an FPSO changing structural characteristics of the unit (placement of a new pressure vessel or storage tank on the platform) influences the mooring system, risers and can compromise the stability of the production unit. As a consequence, an inadequate mooring system design can possibly lead to an increase in the geologic and geotechnical risks.

Changes in environmental conditions, as the direction of wind and currents, as well as changes in the height and frequency of waves, induce movements in the mooring system, in the production risers and also in the ship, which generates second order movements that propagates to the whole system backwards. All those movements should be carefully analyzed to guarantee compatibility with the structural balance of the production unit and with the recommended operational conditions of the production risers. On the one hand, if the mooring system allows large displacements of the production unit, it can simply damage the production risers; on the other hand, the presence of the risers itself helps to weaken the movements of the production unit which positively contributes to the equilibrium of the system. This exhibits an intrinsic coupling among the solutions of the different subprojects, which requires a lot of interactions and discussions among the teams involved. On the one hand, if the mooring system allows large displacements of the production unit, it can simply damage the production risers; on the other hand, the presence of the risers itself helps to weaken the movements of the production unit which positively contributes to the equilibrium of the system. In order to achieve collaboration and interoperability between those subprojects a software-based interface is required.

Another challenge present in OE projects is related to the visualization of large-scale engineering simulations. During the conceptual design phase of an industrial plant, several simulations should be applied to confirm the robustness and feasibility of the project. Some of these simulations may require huge computational efforts to be processed, even for powerful computational grid clusters. Visualization should be as precise as possible in order to provide the user a full understanding of the results of the simulation.

1.3. Problem Solving Environments

Scientists and engineers in many application domains commonly use modeling and simulation codes developed in-house, badly documented, and often with a poor user interface. The code is usually tied to a particular computing environment, and typically only the developers of the code can make effective use of it, reducing the productivity of the team involved in a project or research activity. Another big issue is the lack of integration among those different programs, it is often necessary to convert data back and forth to pass them from one program to another in order to complete several steps of the simulation. This creates an interoperability problem, since in most of the cases, data conversion steps are needed every time a different program is to be run.

The recently proposed concept of Problem Solving Environment (PSE) promises to provide scientists and engineers with integrated environments for problem solving in their domain, increasing their productivity by allowing them to focus on the problem at hand rather than on general computational issues.

A PSE is a specialized software system that provides all the computational facilities needed to solve a target class of problems [GHR94]. These features include advanced solution methods, automatic and semiautomatic selection of solution methods, and ways to easily incorporate novel solution methods. Moreover, PSEs use the language of the target class of problems, so users can run them without specialized knowledge of the underlying operating system, computer hardware or software technology [HGB+97]. PSEs allow users to define and modify problems, choose solution strategies, interact with and manage appropriate hardware and software resources, visualize and analyze results, record and coordinate extended problem solving tasks.

In principle, PSEs can solve simple or complex problems, support both rapid prototyping and detailed analysis, and can be used both in introductory education and at the frontiers of science and engineering [DB06]. In complex problem domains, a PSE may provide intelligent and expert assistance in selecting solution strategies, e.g., algorithms, software components, hardware resources, data, etc.

1.3.1. Collaborative Problem Solving Environments

Collaborative Problem Solving Environments (CPSE) focus on the development of a PSE coupled with collaborative environments to support the modeling and simulation of complex scientific and engineering problems. For LSEP, a CPSE should focus on the development and integration of scientific tools and technologies, coupled with visualization capabilities and collaborative environments to support the modeling and simulation of complex scientific and engineering problems in a collaborative way. Such capabilities enable engineers to easily setup computations in an integrated environment that supports the storage, retrieval, and analysis of the rapidly growing volumes of data produced by computational studies.

Experience in dealing with LSEP design and analysis problems has indicated the critical need for a CPSE with six distinguishing characteristics:

- interoperability facilities to integrate different applications;
- support for human collaboration;
- computing power for numerical simulations;
- visualization capabilities for 3D real-time rendering of massive models;
- transparency for the use of distributed resources;
- advisory support to the user.

One of the CPSE goals is to provide an environment in which visualization and computation are combined. The designer is encouraged to think in terms of the overall task of solving a problem, not simply using the visualization to view the results of the computation [BBB+93].

A combination of CPSE and VR visualization constitutes strategic enablers for a successful data exploration and knowledge dissemination among workers in engineering enterprises. The effective integration of "smart" graphical user interfaces, with some kind of Advisory Support, Scientific Visualization, Virtual Reality techniques, Engineering Analysis and Modeling Tools aid in the automation of modeling analysis and data management for Large Scale Engineering projects. To enhance engineers' ability to share information and resources with colleagues at remote locations, collaborative and real-time technologies integrated into CPSE provide a unified approach to the scientific and engineering discovery and analysis process.

1.4. CEE - Collaborative Problem Solving Environment for Offshore Engineering

According to the above challenges presented for OE projects and based on our previous works on the related area [SRG06, SRG08 and SVR+04] we selected different technologies to compose the CEE, a Collaborative Engineering Environment specialized for OE projects.

The CEE was conceived as a CPSE especially tailored for assisting the control and execution of shared engineering projects involving geographically distributed teams. It should also allow an easy integration of different engineering applications providing team workers with means of information exchange, aiming to reduce the barriers imposed by applications with limited or no collaboration support.

In order to achieve its goals the CEE architecture is a composition of different Computer Supported Collaborative Work (CSCW) technologies to create a useful Collaborative Visualization Environment based on a Virtual Reality Visualization tool, and a Videoconference System; a Scientific Workflow Environment with Grid Computing infrastructure support for executing large engineering simulations; and a Project Management Environment responsible for controlling the overall execution of the project and keeping track of all the information and different artifacts generated during the project entire life cycle.

This integration furnishes to the CEE a collaborative shared workspace [DB92] composed of the following components:

1. ***Collaborative Visualization Environment***
   a. ***Virtual Reality Visualization (VRV) tool*** – a high-performance 3D visualization tool, adapted for collaborative visualization of engineering simulations and massive CAD models. *Awareness* support is also an important feature to make users aware of others activities improving the efficiency of collaboration;
   b. ***Videoconference System (VCS)*** – a VCS to support human communication, providing integrated audio and video channels, chat conversations and desktop sharing, subject to defined control policies;
2. ***Scientific Workflow Environment***
   a. ***Scientific Workflow Management System (ScWfMS)*** – a process-oriented tool to control the execution of engineering

simulations; the collaboration among users takes place while assembling Engineering Workflows, with the help of a workflow graphical modeling tool. The ScWfMS is used by the engineers to orchestrate the execution of different experiments, visualize and validate results. Engineering applications can run on a single machine or on top of a grid-enabled system integrated into the CEE.

b. Grid Computing Infrastructure (GCI)

- ✓ ***Grid Job Submission (GJS) System*** – a job submission and monitoring service to execute engineering simulations;
- ✓ ***Grid Resource Management System –*** a distributed job scheduler and resource management system, used to manage compute intensive batch jobs in heterogeneous environments;

c. Data Access Service – a distributed data access service allowing the retrieval of raw data or aggregate data (time-based raw data e.g.) from different data sources.

3. ***Project Management Environment***
   a. ***Workflow Management System (WfMS) –*** a process-oriented tool to control the execution of the project during its entire lifecycle (workflow project);
   b. ***Document Management System (DMS) –*** a document system to allow the storage of all the documents and artifacts related to the project;

By means of a ScWfMS users are able to orchestrate the execution of engineering simulations as workflow tasks controlled by the workflow engine and executed in the Grid System. Within such a workflow, as its last step, the most important results, according to any specific design criteria, can be selected for visualization in a Collaborative session provided by CEE.

In this thesis and in the current implementation of the CEE we mainly addressed the first two components, giving special attention to the contributions that the Collaborative Visualization can provide to CPSEs. The Project Management Environment was not further elaborated.

1.5. Thesis Main Contributions

The main contribution of this work is to bring together approaches and technologies from different areas, such as offshore engineering, virtual reality, CSCW, and service oriented architecture, to build a collaborative problem-solving environment to help offshore engineers to tackle their LSEP problems.

More specifically, we can distinguish the following contribution for the different areas:

- From the offshore engineering viewpoint, the proposal of using a Scientific Workflow in their project life cycle allows them to have a more structured way to solve their problems.
- Also from the offshore engineering viewpoint, the idea of a CPSE conduces to the creation of engineering tools that can be used by a wider group of users.
- From the visualization viewpoint, the integration of a VRV and Remote Collaboration in the PSE facilitates the information exchange and common understanding of complex problems. Users are compelled to think the overall solution of an engineering problem, using the visualization as a first class tool.
- From the CPSE viewpoint, the approach used for CEE created a real world scenario for an innovative collaborative virtual reality visualization system. This scenario demanded the solution of several integration issues not commonly addressed in similar applications.

1.6. Thesis Outline

The sequence of chapters of the present thesis is organized as follows.

Chapter 2 presents the related works that inspired the concepts of CEE. It also serves as a motivation chapter once it allows us to make some reasoning about the components' purposes for the CEE, presented in Chapter 1. At the end we present a comparison of CEE features and the other systems discussed.

In Chapter 3 we further elaborate the CEE Conceptual Model and the sketch of CEE basic components, which roughly address the problems faced by engineers in LSEP. We also refine the CEE Conceptual model furnishing a more detailed and formal rationale for choosing each one of the involved technologies in order to obtain the CEE SOA (Service Oriented Architecture) Model. We finish the chapter presenting a high-level usage scenario of the CEE from the construction of an Engineering Workflow (possibly in a collaborative way) to the visualization of results in an immersive environment.

In Chapter 4, we present the CEE Detailed SOA architecture. We begin presenting the details of how SOA is used as gluing technology for connecting the CEE components and some of the most important services used by CEE. Then we discuss the usage and integration of Scientific Workflow Management Systems with the VR Visualization Tool, ENVIRON [RCW+06, SRS+08, RCW+09], and also the interconnection with CSVTool [PRS+03, LKR+07], our Videoconference System, used for improving the collaboration capabilities of the CEE. The support of the Grid Computing infrastructure is also discussed.

In Appendix A, which is closely related to Chapter 4, we present the principles of SOA architectures and their basic components, especially the Enterprise Service Bus, a middleware used to seamlessly interconnect applications. The main characteristics of CEE components: WfMS, ScWfMS, VCS and VR visualization system as a subset of a Collaborative Virtual Environment (CVE), and some existing Collaborative Environments is also presented in the Appendix.

In Chapter 5, we present different application scenarios addressed with CEE. As a proof of concept we developed a prototype for each of those scenarios in order to validate the CEE. The results are also discussed.

Finally we present the conclusions and discuss possible future works in Chapter 6. In the Appendix B, we include the list of papers already published related to this thesis.