

# Exploring Immersive Interfaces for Well Placement Optimization in Reservoir Models

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## ABSTRACT

As the oil and gas industry's ultimate goal is to uncover efficient and economic ways to produce oil and gas, well optimization studies are crucially important for reservoir engineers. Although this task has a major impact on reservoir productivity, it has been challenging for reservoir engineers to perform since it involves time-consuming flow simulations to search a large solution space for an optimal well plan. Our work aims to provide engineers a) an analytical method to perform static connectivity analysis as a proxy for flow simulation, b) an application to support well optimization using our method and c) an immersive experience that benefits engineers and supports their needs and preferences when performing the design and assessment of well trajectories. For the latter purpose, we explore our tool with three immersive environments: a CAVE with a tracked gamepad; a HMD with a tracked gamepad; and a HMD with a Leap Motion controller. This paper describes our application and its techniques in each of the different immersive environments. This paper also describes our findings from an exploratory evaluation conducted with six reservoir engineers, which provided insight into our application, and allowed us to discuss the potential benefits of immersion for the oil and gas domain.

## CCS Concepts

- **Human-centered computing** → **Virtual reality**; Walk-through evaluations; Scientific visualization; Gestural input;
- **Computing methodologies** → **Virtual reality**;

## Keywords

Virtual Reality; Immersion; Spatial User Interaction; Reservoir Engineering

## 1. INTRODUCTION

Oil and gas are naturally occurring hydrocarbons found in underground geological formations. Oil and gas reservoirs are subsurface pools of hydrocarbons encompassed by rock formations. The ultimate goal in the oil and gas industry is to

explore these reservoirs and discover efficient and economic ways to produce oil and gas. However, as these petroleum products are trapped in reservoir rocks situated hundreds to thousands of meters underground, reservoir data acquisition is costly. For this reason only limited information is available from a variety of different sources such as seismic geophones, well logs, pressure transducers and core samples.

These different data sources are combined using complex geostatistical methods and expert judgment to develop a realistic three-dimensional reservoir model representing the structure and properties of the subsurface volume [5].

The structure of the 3D reservoir model is often represented by corner point cells, which are irregular hexagonal geometries arranged along three dimensions (i, j, k). Since corner points are not required to be regularly spaced nor spatially continuous, degenerated cells can be produced during the modeling phase, and some may also completely disappear, introducing connections between cells that were not initially neighbors. These properties of corner-point grids make it easy to introduce discontinuities across faces, and therefore include fractures and faults, which are a displacement within one or more rock layers as a result of earth movement.

A model typically consists of thousands to millions of cells, each of which is associated with various properties such as porosity, permeability, and oil saturation. Besides the cell data, reservoir models may also contain information about well trajectories within the reservoir.

Placement of wells in a reservoir has a major impact on the production and economics of the extraction scenario. However, optimal well placement is a challenging issue due to the many variables involved and the typical static and dynamic uncertainties. As a result, engineers must define and assess a number of different placement scenarios. This procedure is called well placement optimization.

The reservoir model is the context in which well placement scenarios are evaluated. To assess the scenarios, simulation techniques such as fluid flow simulations are performed in order to select the best scenario based on the predicted production performance. There are, however, limitations to the number of scenarios that can be assessed using dynamic simulation. The time required by dynamic simulation can be very high, and increases significantly with the complexity of the scenario, the fidelity of the simulation, or the size of the simulation.

Due to this, much research has been devoted to develop fast performance estimators as surrogates for flow simulation. These estimators do not aim to replace a full flow simulation; rather,

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their value lies in rapidly determining parameter sensitivities and screening reservoir models or production scenarios. Hence, among the three contributions of our work, the first of them is an analytical method for performing static connectivity analysis. The second contribution is an application to support well optimization studies using our method as a surrogate for flow simulation.

Furthermore, as modern reservoir engineering and geoscience rely on 3D visual representations of petroleum reservoirs [24], there is increasing interest in using novel technologies to create better visualizations of the reservoirs and develop more intuitive ways to explore them [6] [25] [10]. In particular, as the design and assessment of well trajectories have an inherent 3D spatial nature, we believe immersive technologies may provide an improved medium to view and interact with three-dimensional structures such as reservoir models, wells, and flow behavior graphs. Immersion has been shown to provide real benefits that are useful for our specific demands, including increased spatial understanding and contextual information space, as well as more natural interactions [18] [19].

In order to utilize these benefits, we have developed an immersive application where individuals or groups can design well trajectories, evaluate them in a time efficient manner through static connectivity analysis, and use the learned knowledge to more effectively predict optimal well placements. The third contribution of our work is the exploration of different immersive interfaces to support more effective visualization and interactions in our application.

A primary goal of our application is to create an immersive system that fits engineers' needs and preferences for performing exploratory well placement analysis. However, we understand that we will only be able to achieve this if we meet the requirements of those that would be using the tool. For this reason, in this work we focused on interviewing subject matter experts about their requirements regarding well exploration techniques and immersive well exploration systems. We hope this will inform better design for our application and other such applications in the future.

This paper describes our analytical approach for performing static connectivity analysis. It then introduces our application and the techniques that were implemented for creation and assessment of well trajectories. Lastly, this paper describes an exploratory evaluation conducted with six petroleum engineers for two main purposes: to gather their thoughts regarding our techniques and brainstorm ideas for future development; and to collect their feedback and preferences regarding the immersive aspects of the application.

## 2. RELATED WORK

### 2.1 On Reservoir Engineering

As mentioned in [24], the development of three-dimensional visualization tools represented a real breakthrough in reservoir geosciences and engineering. Also, allowing real time manipulation greatly improves the understanding and eases analysis of the model [5]. Currently, several commercial software packages are available for reservoir simulation and visualization, and they have become integral to reservoir engineering. Among the available commercial solutions, GUI-based desktop systems such as CMG Suite [1] and Petrel [4] are the most common.

These solutions provide traditional visualization and interaction techniques for assessing reservoir models and monitoring oil and gas production. However, there has been a growing effort in some

areas of reservoir engineering and geosciences to incorporate novel visualization techniques to improve the ease, speed and accuracy of visual analysis tasks. For instance, [6] proposed the use of a cutaway illustrative technique to improve the inspection and analysis of properties in reservoir models. This technique emphasizes important structures or parts of the model by selectively discarding occluding parts while keeping the contextual information in view.

Traditional desktop applications have clearly demonstrated value by improving the efficiency of reservoir modeling and analysis. However, desktop display systems provide a limited opportunity for collaboration between domain experts. It is widely acknowledged in the industry that collaboration is essential throughout the oil and gas exploration and production (E&P) life cycle [24]. To serve this need to perform group work and analysis and to showcase information, technologies have been developed to facilitate collaborative reservoir analysis and provide a shared awareness of the reservoir.

As an example, [25] proposed a set of techniques for supporting the visual exploration of reservoir simulation models in tabletops. The techniques included a method to probe individual cells and display property values; "splitting" and "peeling" gestures to view the inside of the reservoir while maintaining context; and a touch tap to select a well and to activate a cutaway view that removes cells occluding the chosen well path. As another example, [22] explored three techniques to create well paths in tabletops. One technique, called the 2D planes approach, allows the user to select a plane (xy, yz, or xz) and rotate it along its axis (x, y, and z, respectively) using a rotation widget. The user can then create a well path on the plane using a finger motion.

These approaches address the collaborative and interdisciplinary needs of an oil or gas development project. However, all face the fundamentally difficult problem of facilitating complex spatial tasks such as defining a three-dimensional well trajectory within a two-dimensional space such as a desktop screen or a touch surface.

By using an associative and spatial system for these 3D tasks, it is possible to present a 3D view that people are familiar with [15] and that is natural and intuitive when working with 3D geological datasets such as petroleum reservoir models. For this reason, there have been efforts that either explore tangible user interfaces (TUI) or immersive virtual environments (IVE) in reservoir geoscience and engineering.

Snakey [10] is a collaborative TUI to support designing and manipulating 3D well paths for reservoir engineering. ReservoirBench [23], is an interactive tangible workbench designed to teach basic geological science and engineering tasks, such as arranging seismic planes or creating vertical and horizontal wells.

The potential of immersive environments has also been investigated, including exploration of how immersive features can benefit the oil and gas domain [16] [18]. For example, the performance of different immersive environments for well path editing has been examined [19]. The authors compared task completion times and correctness between participants using an immersive CAVE-like environment and those using a desktop system. The immersive environment provided stereo and head-tracked viewing, and used a tracked wand for navigation and direct pointing. The desktop version of the application used a stereoscopic computer monitor with a mouse, keyboard, and virtual widgets to support interaction. Although this work found speed and accuracy improvements in the immersive environment

when editing the path of a new well in a mature field, the differences in display or interaction techniques that may have caused the performance differences between the two conditions were not explored.

## 2.2 On Immersion

Given the inherent spatial nature of the tasks performed when designing and assessing well trajectories, we believe that some immersive technologies can provide improved visualization and interaction interfaces for these tasks. An important consideration however is that different immersive technologies may provide different benefits [20]. Some of these benefits may be particularly helpful for well planning in the oil and gas domain. These include enhanced spatial understanding, increased information space, and more natural interactions.

One major benefit of immersion is increased spatial understanding. As an example, [20] evaluated small-scale spatial judgments, which requires careful visual inspection of objects that are small relative to the scale of the environment. The authors evaluated the effects of field-of-regard, stereoscopy, and head-tracked rendering on the performance (time and number of errors) of the task of identification of collisions and gaps in complex underground cave systems. The results suggest that the addition of the higher fidelity system features support performance improvements in making precise spatial inspections of complex three-dimensional structures. Correctly making such judgments is important for well planning, which includes tasks such as evaluation of the geometry of objects, identification of object intersections, and determining whether different paths will cross each other or if open spaces exist between objects.

Studies have evaluated spatial understanding tasks that require participants to visually trace paths within three-dimensional graph structures [26]. In general, the findings suggest performance improvements in path-tracing tasks due to the addition of either stereo or head tracking, with the best performance achieved using a combination of both.

A second potential benefit of immersion relates to an increase in information space. Although large, high resolution desktop displays are becoming more common, the amount and variety of data that can be displayed and analyzed by a group of collaborators is limited. An immersive environment, in contrast, delivers increased field of view and field of regard which facilitates a larger information space so a larger amount of information and context may be considered at the same time.

Well planning should ideally integrate all of the available geophysical and geological data in the same visual environment. This data may include for example seismic data, horizons, faults, cell attributes, existing well paths and log data and often much more. Thus, immersive display systems have the potential to provide a common three-dimensional space to visualize and evaluate this often complex, multidisciplinary data in a clear fashion, so any inconsistencies or errors in the data, or in the geologic interpretation, are obvious and important insights may be more easily achieved.

Further to this, immersive features such as head tracking allow users to change the view using familiar physical movements such as walking, leaning, crouching, or turning, and provide the opportunity for more natural interactions with data, freeing the user to focus on the problem at hand rather than the tool.

## 3. WELL PLANNING

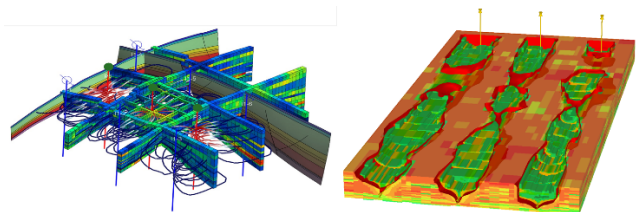
In reservoir engineering, well planning refers to the definition and evaluation of well placement. The placement of wells has a major impact in a development project. Optimal well placement improves the long-term and short-term performance of wells by maximizing hydrocarbon recovery, extending well life, and in cases of pressure support from injection, reducing water production.

However, optimal well placement is challenging to determine due to the many variables involved and the static and dynamic uncertainties. Variables include the location, trajectory, and perforations of the well, the type of the well, the flow rate of the well, and the type of enhanced oil recovery, if any. These many parameters interact with each other, often in complex ways, resulting in a large solution space that must be searched to find an optimal outcome.

For this reason, engineers must define and assess a number of different placement scenarios based on the expected reservoir response and production in order to select optimal scenarios. During optimization studies, the engineer changes parameters prior to simulation in search of an optimal scenario. Typical parameters that would be changed include the number of wells, the spacing between them, the locations and trajectories of the wells, the introduction or modification of injection fluids and possibly many others.

### 3.1 Using Dynamic Flow Simulation

Reservoir fluid flow simulation is commonly used to calculate the expected outcome of each placement scenario so that they may be evaluated. The scenarios are evaluated based on the economic production of petroleum products. After the simulation results are calculated, the engineer typically executes two analysis tasks: a) The production profile. This is a production  $x$  time graph showing how metrics such as oil production are expected to behave through time. b) The flow behavior. In existing reservoir simulation software, flow simulation results are typically represented through visualizations such as isosurfaces or streamlines (Figure 1). Typically, a slider widget is used to move between different time periods to observe how the oil flow changes through time. If there is a part of the reservoir where the flow does not reach, the engineer may try to understand why this happened by evaluating the geological features – e.g., “*is there a fault or fracture in this region preventing oil to flow?*”, and the reservoir properties – e.g., “*is the permeability low in this region that is preventing the oil to flow?*”.



**Figure 1:** Isosurfaces (*right*) and streamlines (*left*) are commonly used to interpret flow simulation results.

Dynamic flow simulation may lead to accurate production predictions; however, the primary disadvantage is that this process is computationally expensive. Hours, days or even months may be required depending on the size of the model, the complexity of the model and the accuracy desired. This is a significant limitation for well optimization as the engineer is limited to run only a small

number of flow simulations before choosing the “optimal” well placement scenario.

For this reason, alternative approaches are being investigated that use heuristics to find promising candidate well placement scenarios, and then run flow simulation on only the most promising scenarios. Typically, these approaches focus on using a combination of static geological reservoir properties to predict the approximate dynamic reservoir flow behavior. Despite a loss of accuracy due to the simplification relative to numerical simulation, this approach can provide very useful information relatively quickly. This is the approach taken in our application.

### 3.2 Using Static Connectivity Analysis

There is research showing that connectivity is a reservoir property that strongly correlates with the efficiency of hydrocarbon recovery [12]. In primary recovery, if a part of a reservoir is not connected to a producing well, then the hydrocarbon present in that region cannot be recovered. In secondary recovery, both producing and injecting wells need to be connected to the same reservoir geo-body in order to create sweep zones and, thus achieve better production efficiency [17].

A significant amount of research has been devoted to developing analytical methods that quantify reservoir connectivity using static geological properties [8] [11] [21]. This connectivity measure, in turn, is used as a fast reservoir performance estimator in different activities in oil and gas E&P such as well planning, comparison between finer and coarser models to evaluate whether structural and stratigraphic characteristics have been preserved during up-scaling, to rank different geological realizations for reservoir simulation, to name just a few possibilities.

Despite its relevance, to our knowledge, current geologic modeling and reservoir simulation software do not offer a means to assess connectivity in a way that is computationally efficient, interactive, and visual. Thus, our work proposes a novel application to support well optimization studies. Our application uses static connectivity analysis to serve as a proxy for flow simulation to provide performance estimation of well placements.

### 3.3 Our Approach

Our method to perform static connectivity analysis first converts the reservoir grid to a graph. The cells used in the reservoir model in which each cell has one or more properties, are converted to a node and edge-based representation.

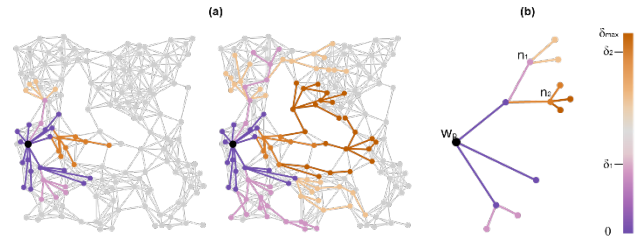
In this representation, each node has the same cell properties; however, the edges are associated with new, additional properties related to the connection between nodes. One such edge property is transmissibility. The term transmissibility as used in reservoir simulation refers to a constant value characterizing the flow connection between two adjacent grid cells. The transmissibility between two nodes represents how readily fluid flows from one node to another. The inverse of transmissibility is also an edge property and referred to as the “edge resistance”, or “edge cost”.

Dijkstra’s shortest path algorithm is then used on the graph to perform connectivity analysis for each well perforation along the well trajectory.

This gives the least resistive path from a perforation to a target node, taking into account the resistance of the edges along the path connecting the source to the target node. As illustrated in Figure 2, the method is applied in order to find the least resistive path between a perforation node and all other nodes that are reachable from the perforation. A node is not reachable when no transmissible path exists connecting the node to the perforation.

After running the shortest path method on a well perforation node, the output is: a) A “connectivity graph” that contains all nodes (cells) connected to the perforation. b) For each connected node, the least resistive path connecting it to the perforation, and the cumulative cost along this path – that is, the minimum cost to go from the perforation node to this node.

The minimum cost parameter associated with each connected node is referred to as “delta time”. Not to be confused with absolute time, this measure represents relative time to reach a node. For the scenario illustrated in Figure 2, a perforation node  $w_p$  is connected to two nodes,  $n_1$  and  $n_2$ , with respective delta times  $\delta_1$  and  $\delta_2$ . If  $\delta_1 > \delta_2$ , it means that the path connecting  $w_p$  to  $n_1$  is less transmissible than the one connecting  $w_p$  to  $n_2$ . Thus, the oil in  $n_2$  would be produced before  $n_1$ .



**Figure 2:** Shortest path calculation (a) along with minimum cost (delta time) parameter associated with nodes (b).

After running the shortest path in each well perforation, the user may then specify a threshold value,  $\delta_{th}$ , to filter out connected nodes that are not connected strongly enough to be reached within the threshold delta time. The connectivity measure for a well perforation is calculated as the sum of the hydrocarbon pore volume (HCPV) of each connected cell,  $c$ , that has  $\delta_c \leq \delta_{th}$ . The overall connectivity measure of the well is the sum of the connectivity measures of all perforations in the well.

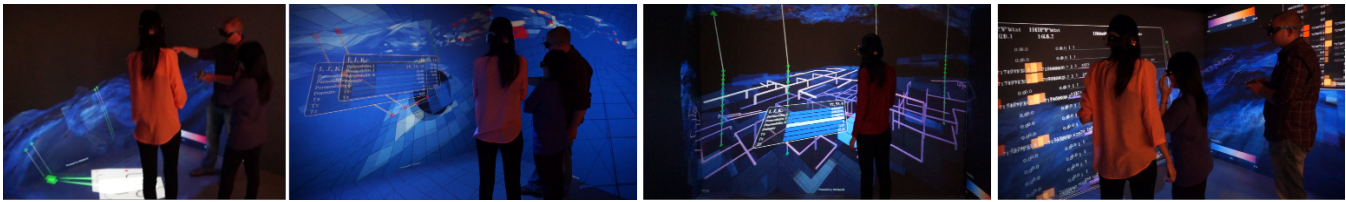
## 4. APPLICATION

Our work also involves the development of an application to support well optimization studies. This tool uses our method to perform static connectivity analysis as a proxy for flow simulation. Further to this, the application is tested in three immersive environments, as can be observed in Figure 3.

This section describes the software and hardware used for our application. We then describe the application features applied in each of the interaction interfaces: a gamepad and a leap motion controller.



**Figure 3:** Our application explores three immersive environments: a CAVE with a tracked gamepad (left), a HMD with a tracked gamepad (center), and a HMD with a leap motion device attached to it (right).



**Figure 4:** Illustrations of some of our techniques applied to the CAVE environment. From left to right: (1) vertical and (2) free-form well creation, (3) connectivity graph analysis, and (4) analysis of analytical tables of the connectivity.

## 4.1 Software Specifications

Our tool is a Unity application written in the C# programming language. A key consideration when selecting Unity was the relative ease with which cross platform applications may be developed.

Another consideration was the availability of MiddleVR [3], a library that makes it relatively simple to develop an application that works in different VR environments. MiddleVR provides an abstraction layer for different aspects of a VR application, such as display and interaction devices, stereoscopy, and clustering. These aspects may then be defined in a configuration file, simplifying deployment in different environments. Unity also integrates with the Hovercast VR toolkit [2], which provides a customizable menu interface for virtual reality applications.

## 4.2 Hardware Specifications

As illustrated in Figure 3, the application runs in three immersive environments. One is a CAVE with a tracked gamepad controller. The CAVE system consists of four screens powered by projectors each with a resolution of 1280x1024. The system supports active stereoscopy using Volfoni Edge VR 3D glasses. The gamepad controller is a Logitech F710. Tracking of both the stereo glasses and the gamepad is accomplished using eight Vicon T160 infrared cameras. The second environment consists of an Oculus Rift DK2 with a tracked gamepad. The same model of gamepad (Logitech F710) and the same Vicon system are used. The third environment consists of a Leap Motion controller along with the same Oculus Rift DK2.

## 4.3 Interactions Using Gamepad

### 4.3.1 System Control

When using the gamepad, the application uses a 1-DOF hierarchical graphical menu. This view-dependent menu appears when the user presses the *Y* button on the gamepad. The user can then select a menu item by hovering it and pressing the *A* button on the gamepad.

The menu is used to select tasks such as deletion or creation of a certain type of well trajectory, and to perform basic functions such as filtering cells based on property values or modifying properties displayed.

### 4.3.2 Basic Manipulations

The user may use the joystick on the gamepad to rotate, translate, or scale the reservoir. The left stick allows the user to translate the reservoir on the *x*- and *z*- axis; while the left and right bumpers translate on the *y*- axis. The left and right triggers allow the user to scale the reservoir model up or down. Finally, the right stick allows the user to rotate the reservoir around the *x*- and *y*- axis.

The user can also toggle transparency and visibility of the reservoir cells by using the start and back buttons, respectively. Setting the reservoir semi-transparent or invisible allows the user

to view internal structures within the reservoir such as the well trajectories and their connected graphs. Semi-transparent mode allows a contextual view of the reservoir surface to be maintained.

### 4.3.3 Cell Probing

To be able to select a certain cell and view information only about that cell is a feature frequently used by reservoir engineers and geoscientists, and is common in commercial software. This feature is called cell probing and it allows a user to understand small scale data variations. This is an essential tool especially when inspecting grid cells to determine a candidate well trajectory. In our application, we provided a 3D, immersive version of this feature.

In order to probe cells, the user presses and holds the *A* button on the controller. This action activates a small, white probing cube close to the controller that mirrors its position and orientation. The probing cube acts as a three-dimensional cursor and whenever the cube collides with a cell, the grid cell is selected and rendered along with a small view-dependent window with information about the cell such as the *i*, *j*, *k* coordinates of the cell and properties related to flow efficiency such as permeability in *i*, *j*, *k* directions; porosity; and transmissibility in *i*, *j*, *k* directions.

A view-dependent, volumetric transparency lens appears around the cube in order to overcome the issue of surface occlusion when probing grid cells from outside of the reservoir surface. The lens allows the user to see into the reservoir and select internal cells. The lens removes grid cells surrounding the probing cube and only displays the reservoir's wireframe lines close to the cube and the cell being probed.

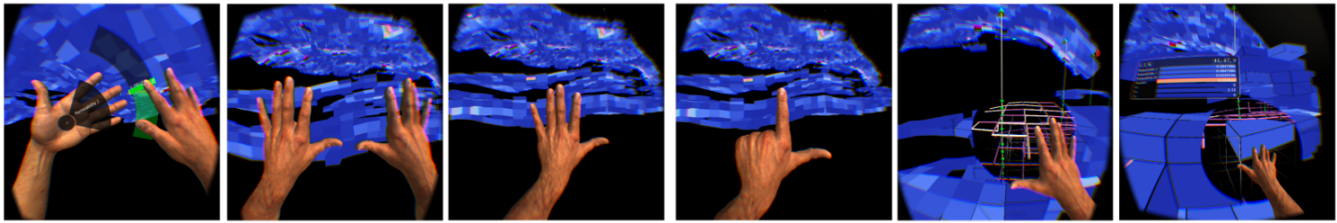
### 4.3.4 Well Trajectory Creation

As illustrated in Figure 4, there are two types of wells that may be created: vertical and free-form wells. For vertical wells, the user uses a ray attached to the gamepad to highlight cells on the surface of the reservoir. By pressing the *A* button on the gamepad, a vertical well is placed and a well perforation is created in each of the cells in the column below the currently highlighted grid cell.

When creating free-form wells, the user must select each of the perforations in the the free-form well. By holding down the *B* button on the gamepad, the probing technique is triggered and, whenever the button is released, the first well perforation is created on the currently selected cell. By repeating this process, other perforations are defined for the well. Re-selecting one of the perforations signals the completion of the well path.

### 4.3.5 Well Trajectory Analysis – Graph

As previously described, a connectivity graph is defined for each perforation along each well. In turn, each node included in a connectivity graph has an associated connectivity measure called “delta time”. This measure indicates how strongly connected cells are, thus indicating the relative time that would be required for oil to flow from a cell to its associated well perforation.



**Figure 5:** Illustrations of our interactions applied to a reservoir model while using gestures. From left to right: (1) property filtering through hand-menu; (2) scaling; (3) rotation; (4) translation; (5) alpha lens and (6) information window for probing.

A diverging color scheme is applied to the edges of the graph in order to encode “delta time” data. Edges with a deeper purple color have a lower delta time value and thus a stronger, more transmissible connection between the perforation and the cell. A brighter orange indicates a higher delta time value and thus a relatively low connection to the cell.

The graph is represented as a tube that radiates spatially from a perforation cell and connects the centroids of each pair of adjacent cells. In addition, the graph is rendered within the reservoir model as this facilitates the evaluation of the stratigraphic and geological factors influencing the connectivity between cells. For example, in a scenario where the connectivity changes abruptly, the user may use the transparency lens or set a semi-transparent reservoir in order to look for faults, fractures, or gaps on the cell geometries that may be acting as a barrier to the flow. The user may also probe cells along the edges of the graph where the connectivity suddenly changed in order to examine whether geological property values are negatively impacting the connectivity (see Figure 4).

Also, as previously mentioned, the user can define a delta-time threshold value in order to filter out cells not reached by flow at that time limit. The application uses a 1-DOF slider widget that ranges from zero to the maximum existing delta time. In order to define the threshold, the user places the ray pointer above the slider, holds the *A* button on the gamepad, and drags the ray along the slider. The spatial graph then changes accordingly to the user specified threshold.

Furthermore, as a reservoir model may contain multiple wells, and each well may have multiple graphs, the view may become cluttered. To help eliminate clutter, the user may press and release the *A* button on a well head. This selection causes only cells connected to the well to be displayed. Similarly, by selecting a specific well perforation, only cells connected to that perforation will be displayed.

#### 4.3.6 Well Trajectory Analysis – Analytics

For each new well, along with the connectivity graphs, a tabular panel is created to display analytical connectivity data associated with the well (see Figure 4). The table contains four columns, and each row shows data associated with a well perforation. The last row shows cumulative data for the entire well.

The first column of the table shows the *i*, *j*, *k* coordinates of the perforations. The second column displays the total drainable hydrocarbon pore volume (HCPV) of all connected cells – that is, the cells associated with the nodes that compose the connectivity graph for the perforation. The third column shows the total HCPV of all connected cells that have arrival time below or equal to the currently selected time threshold. The last column shows the distribution of time for all connected cells.

The user may arrange each panel individually. Panels may be expanded or compressed so that they may be brought to the

foreground of attention or minimized to reduce information clutter. To scale a panel up or down, the user hovers over it with the ray and presses the up or down buttons on the d-pad. Panels may be positioned anywhere in space, stacked on top of each other, sorted and organized according to the user’s preference. To translate and to rotate a panel, the user places the ray on it and holds the *A* button on the gamepad in order to select the panel. Then the panel follows the movement of the tracked controller.

In order to decrease the physical effort of arranging panels, the mapping between the movement of the controller and the selected panel is not 1:1. When moved using the controller, the panel translates by a factor of 5:1 and rotates by a factor of 2:1 relative to the physical translations and rotations using the controller. These factors were empirically determined but we believe them to be effective in reducing physical workload while maintaining the required precision to efficiently perform the tasks.

### 4.4 Interactions Using Leap Motion

When using gestures as an interaction interface, the user has access to only a subset of features: setting a system control menu, manipulating the reservoir model, and probing the grid cells. This reduced feature set was implemented to collect initial feedback regarding gesture controls that could help designing the more complex features, such as the well trajectory creation.

#### 4.4.1 System Control

When controlling the application with the leap motion device using the Oculus, the application uses a 1-DOF hierarchical graphical menu attached to the user’s left hand. The arc-shaped menu appears whenever the user rotates the left palm towards the face. The user can then select the menu items using the index finger of the opposite hand. To select an item, the user moves a fingertip to the menu item and hovers briefly.

#### 4.4.2 Basic Manipulations

When designing the rotation, translation, and scale operations, one important interaction design principle that we considered is that gesture-based interactions should be initiated with specific gestures that are rarely a part of casual movements. For this reason we devised initialization (or “trigger”) motions from which an action may be initiated. After detecting a gesture pattern, the gesture-related action is triggered provided that the user performs a gesture motion above a certain speed threshold.

As depicted in Figure 5, to scale the reservoir model the user must put both hands up with all fingers extended and with palms facing outwards. In order to trigger the scaling operation, the user must then move either forward or backward fast enough to surpass a pre-defined speed threshold. If the movement is fast enough and is forward (that is, positive in the *z*-axis), the reservoir is scaled up equally in *x*-, *y*-, and *z*- axis; if the movement is fast enough and is backward (that is, negative in the *z*-axis), the reservoir is scaled down equally in all axes.

To rotate the reservoir the user must extend all fingers in the left hand with the palm facing outwards, while to translate the reservoir the user must extend the thumb and index fingers of the left hand with the palm facing outwards. When the operations are triggered, the hand motion is then performed per axis: given the hand motion vector  $v = (v_x, v_y, v_z)$ , the filtered, per axis vector consists of the same vector with its two lowest values substituted to zero.

To toggle the transparency and visibility of the reservoir, the user uses the gesture based menu described earlier.

#### 4.4.3 Cell Probing

As illustrated in Figure 5, the user extends all fingers in the right hand with the palm facing outwards to trigger the probing function. The user can then move the fully-opened hand to probe different cells. When using gestures, no small white cube is used as a cursor. Instead, the right index finger acts as the three-dimensional cursor. The right index is surrounded by the transparency lens and whenever it collides with a cell, this grid cell is selected, causing it to be rendered along with the data window.

## 5. EVALUATION

Our evaluation sessions were divided into two parts: an evaluation of the features of the application and an investigation into the suitability and preferences of engineers with regards to different immersive environments when performing the inherently exploratory tasks of the application. Throughout each session, we performed a series of standardized demos and interviews with each participant.

We conducted one pilot session with an expert reservoir engineer from our research group who was not involved in the design of the application. The other five sessions were with external reservoir engineering experts. Each of the six evaluation sessions lasted between 60 and 90 minutes.

Sessions started with a description of the goals of the evaluation session: feedback regarding the features of the prototype, as well as feedback regarding the different virtual reality mediums to be presented. Next, participants were asked to answer a questionnaire to understand their expertise, as well as their previous experience relevant to the domain.

### 5.1 On the Application

The features of the application were first demonstrated using the CAVE environment. Since most of the participants were new to virtual reality technology, we were aware that the lack of familiarity could create an unfavorable or intimidating experience. To reduce biased results and allow feedback without having to account for lack of training, each of the features were demonstrated by one of the two session facilitators. The facilitator used the tracked stereo glasses and thus had the optimal perspective and controlled the application using the gamepad. Participants used untracked stereo glasses and were requested to remain close to the facilitator to ensure their view perspective was not distorted.

Each of the implemented features were then introduced and explained in the same sequence presented in this paper: (1) basic manipulations, (2) cell probing, (3) vertical and free-form well trajectory creation, (4) well trajectory analysis using the connectivity graph, (5) well trajectory analysis using the connectivity analytics panels.

At the end of each of the five demo sections, participants were asked to provide their opinion on the feature they had been shown in that section, and to reflect on its usefulness, potential problems and suggestions for improvement. After all the five features were demonstrated, we asked them for suggestions for other potentially useful features, and then asked for additional comments if there were any. Sessions were video recorded for further qualitative analysis.

### 5.2 On the Immersive Mediums

After the demonstrations and interviews about the features of the application in the CAVE, a preliminary inquiry into other immersive display and other interaction devices were performed. The participants were exposed to the same application running in an Oculus Rift DK2 with the same tracked gamepad controller as used in the CAVE. Then, participants were asked to reflect upon the differences they noticed between their traditional desktops, the CAVE, and the Oculus; what advantages or disadvantages they noticed about each environment; which environments they preferred and why, as well as any general comments.

Following this, the participants were introduced to the same application using an Oculus Rift DK2 along with a Leap Motion controller. The participants were then asked similar questions to gather feedback comparing their traditional keyboard and mouse interface, the gamepad, and the Leap Motion controller.

### 5.3 Participants

Six individuals took part in this study: four males and two females. Their age ranged from 26 to 37 years old. All of them had undergraduate degrees and one or more graduate degrees in Petroleum Engineering. Five of them were enrolled in a Ph.D. Program in Petroleum Engineering and one was a post-doctoral scholar. Five of them had between one and seven years of professional experience as reservoir engineers. One of the participants was currently employed as a reservoir engineer and two others were currently working in a reservoir simulation software company.

## 6. RESULTS

### 6.1 On the Application

#### 6.1.1 Cell Probing

When asked about the usefulness of probing, participants claimed the probe was one of the most common functions used – e.g. “*I probe all the time*”. They appreciated the functionality of the transparency lens associated with the probe as it allowed them to efficiently see both the property values in the reservoir and the well configuration in 3D. When asked to compare with existing desktop software, participants commented that using existing tools it is required to either visualize the well path inside the reservoir across multiple 2D cross sections or view a transparent overview of the 3D reservoir model.

#### 6.1.2 Well Trajectory Creation

When asked about the usefulness of the probing tool while selecting the well path, we received several different comments. One user commented that only seeing the selected cell is preferable. The main advantage of this, according to the user, is that the 3D geometry of the cell can be clearly observed to avoid the selection of shapes that could cause problems with the numerical simulation such as “pinch” cells. However, another participant commented it would be preferable to have more contextual information surrounding the selected cell. This user

suggested an improvement would be to display the entire column or an adjustable number of cells neighboring the selected cell.

When asked about the well path creation tasks, participants requested to be able to remove well perforations – e.g. *“sometimes I already know which layers of the reservoir have oil, so I’ll perforate only those layers”*, *“the connectivity analysis shows me useless perforations, so I’d like to remove them”*.

### 6.1.3 Well Trajectory Analysis – Graph

When questioned about the usefulness of the connectivity graph, we received positive comments – *“this is amazing. It’s like I can see where the oil comes from”*. Some participants praised the benefit of being able to quickly assess the region that can be covered by a well. They claimed that this would help them find locations that cover larger areas. They also commented that the connectivity graph would help with finding locations in the reservoir not covered by existing wells. Users claimed this analysis would help them evaluate how many wells might be needed to cover parts of a development field.

Other participants praised the ability to see the connected cells associated with each perforation, as this would help them more accurately design a perforation scheme that was efficient and without perforations that are not needed or even detrimental to recovery.

Some participants noted as a limitation of our application that a higher contrast color scheme should be used for the graph encoding to improve clarity.

When prompted for ideas for improvements, one participant suggested it would be useful to highlight locations where the connectivity changed abruptly so barriers to flow could be easily identified. Another participant mentioned that it would be interesting to also display a contour style visualization of the region connected to the well to provide a *“general trend”* or a *“big picture of the behavior of flow”* view as opposed to a *“detailed”* view using the connected graph.

Also, since wells are often associated with specific drainage areas, one participant requested a feature to filter the connectivity graph according to the distance from the well – *“when wells are producing, each well is associated with a drainage area. (...) it’s important to see the volume connected to the well only in its share region”*. One participant also mentioned that *“if we have two wells not too far away from each other, it’s important to see the location and (delta) time when the regions connected to the wells start to interfere with each other”*. This is because if two wells are producing, each one has an amount of recoverable oil volume associated with it. However, if there is interference, wells may not be recovering the expected oil production since they might only produce from the region up to where interference occurs.

The same participant also suggested it would be useful to display the shortest path between a user selected cell and the associated well along the spatial graph. According to this individual, this would provide a visual indication of permeable channel deposits or saturation fronts.

### 6.1.4 Well Trajectory Analysis – Analytics

The panels displaying analytical connectivity data were well received – e.g., *“this is very good as it gives a snapshot of the performance of each perforation and the entire well”*. All participants felt it was very important to have both the visual and analytical data available so they could also access detailed information. Users appreciated the ability to move and organize the panels in three dimensional space, but some requested that

there be a way to help organize them, such as being able to set them to hover near their associated well, or automatically stack or sort based on user defined criteria.

One participant indicated it would be useful to be able to select ranges of the histogram in order to see the associated connected cells in the spatial graph. This action, in turn, would help define the coverage areas for different wells and the inter-well spacing between them – e.g., *“if two wells are producing and I see the connectivity graphs overlapping, I would need to decide how much to move one of them further away”*.

### 6.1.5 Further Feedback

When asked about any additional comments or suggestions, most of the participants requested the ability to save well trajectory and perforation information to a file format that could be loaded in commercial reservoir simulation software. Requests for the tool to read in trajectories and perforation data from file formats commonly used by commercial reservoir simulation software were also common.

Some participants claimed it was important to edit well trajectories and perforations so that different well configurations could be easily evaluated. Further to this, one participant suggested a feature to support the comparison between two or more configurations of the same well. Another participant indicated it would be useful to be able to save and recall well configurations, so that a saved well configuration could be *“pasted”* into arbitrary locations in the reservoir as often as needed.

One participant suggested the current well connectivity analysis tool be extended to *“inter-well connectivity analysis”*. The participant commented that for mature fields, engineers must commonly decide on the placement of injector wells based on the already existing producer wells. Thus, the evaluation of the connectivity between a pair of producer and injector wells would be even more helpful for this scenario.

## 6.2 On the Immersive Mediums

### 6.2.1 CAVE and Oculus

Following the interview regarding the application features, we captured each participant’s impressions and preferences regarding two immersive environments, the CAVE and the Oculus Rift, using the same gamepad controller.

Participants claimed the visualization of the reservoir was clearer when using the Oculus Rift. They reported that the perception of details was better than in the CAVE. Most participants (five out of six) appreciated increased detail, relating that to the feeling of actually being immersed in the environment – e.g., *“it makes me feel more ‘into it’; as if things are closer”*.

One of the participants claimed that what they saw in the Oculus looked more familiar – *“things looked more aligned to what I know”*. On the other hand, another participant argued that *“immersion on the Oculus is so high that it may complicate the analysis of the reservoir as a whole”*. The participant was alluding to the fact that the field of view is narrower in the Oculus compared to the CAVE system and this was a hindrance to visualizing the reservoir – *“we are used to have a wider vision”*.

When queried about the usefulness of both devices, most of the participants claimed they would prefer to work with the Oculus if they are working on their own; however, they would prefer to work with the CAVE if there are more individuals involved and the purpose is to collaborate with co-workers, to showcase



projects, or to make joint decisions. The participants did claim they tend to work individually, but acknowledged that a device for collaborative work (*“which is common in industry”*) is very important.

When queried about difficulties and limitations, one of the participants claimed they *“felt more in control with the Oculus when compared to the CAVE”*. This participant pointed out that one of the shortcomings of the CAVE is that *“it shows things according to a particular person (...) this may be the reason why I have felt some eye fatigue”*. Another difficulty mentioned by two participants was regarding comfort while using the Oculus Rift. One of them mentioned that *“technology may need to advance to be more practical”* after noting the heaviness of the Oculus compared to the glasses used in the CAVE.

As a suggestion for improvement, one participant claimed that it would be ideal if more users could *“control the environment”* when using the CAVE or *“share the environment”* when using the Oculus. This participant suggested that equal autonomy for users in the virtual environment would improve both the quality of the experience and the potential for collaboration.

### 6.2.2 Gamepad and Leap Motion

Finally, we captured impressions and feedback regarding experiences when using the Oculus Rift with two different interaction interfaces. Participants interacted with the application using a gamepad first, and then hand gestures.

All participants claimed that gestures were more natural and intuitive for them – e.g., *“your hands is part of you, so you know how to control it”*; *“(your hand) it’s you. (...) with the gamepad, you have the buttons as an additional layer”*. Nonetheless, they also claimed there was a learning curve and some period of adaption would be necessary – which they did not think was problematic however.

Although users agreed that gestures would feel more natural, they acknowledged that using a gamepad provided benefits that gestures did not. One of the participants noted that using gestures meant the hands were required to be *“fixed in a particular spot”* – that is, on the space covered by the gesture and motion sensor; whereas the gamepad allowed more flexibility. The same participant also noted that the use of gestures seemed to lead to some glitches during the interaction process; something the user did not notice when using the gamepad.

Another participant claimed that when probing, the gamepad allowed users to see and reach farther than hands and arms physically allow – *“most of the time, I probe multiple cells in different regions, so I don’t want to be too close to a cell”*. The user also claimed fatigue as another potential problem with using hands – *“probing is a feature that I use all the time, so having my arms resting on the chair is more convenient”*. The participant suggested that an improvement would be to attach a cursor to the index finger in order to probe cells further away. In spite of the drawbacks mentioned, this participant claimed they would prefer to use gestures rather than the gamepad.

## 7. DISCUSSION

### 7.1 On the Application

There were several suggestions and many positive comments regarding our application. Many of them were related to the connectivity analysis. This shows that even though static connectivity analysis was a new approach for them, they understood its purpose and value. Not only were the participants

pleased with the connectivity technique, but they also claimed that the three dimensional perspective in both environments was superior to their traditional desktop environment. These results support our belief that immersion is indeed beneficial for our application.

Interestingly, several participants provided feedback that echo some of the challenges VR has historically faced in the field of oil and gas mentioned in [16]. For instance, many participants requested the ability to save and load well trajectories, fault information, and other data from a software familiar to them. During the feedback sessions, it was clear that it was important for participants to easily transfer data between their existing workflows and our tool. Lack of compatibility with software packages had been identified in [16] as a barrier to the use of VR in oil and gas.

For this reason, we chose to use VTK as our data format since it is widely used. Also, we created tools to convert reservoir data formats to the VTK format we use, increasing the ease of importing data into our tool. However, we have not yet built support for saving or loading well trajectories. This could be added relatively easily and clearly it is desirable to do so.

### 7.2 On the Immersive Mediums

Regarding immersive mediums, [16] noted the fact that accessing a large system that would require users to leave their desks would be a barrier to widespread use of VR in oil and gas. However, there are currently high quality virtual reality devices such as the Oculus Rift and the HTC Vive, and vendors are offering enterprise class VR workstations. Hence, it is now possible to affordably have a VR headset at a workstation for individual use or remote collaboration, and to move to an advanced visualization platform such as a CAVE or CAVE variant only for co-located collaboration, training, and demonstration to groups. Many participants mentioned they would prefer to use HMDs such as the Oculus Rift for individual work whereas they would rather use the CAVE when performing collaborative work. Our CAVE is relatively low resolution, but a high resolution system should address the concerns regarding clarity that were expressed.

Participants appreciated the ability to move between the head mounted display and the large scale immersive display, but were afraid that would require them to go through two types of training. There are many different display and input devices, and to provide a solution that has a consistent user experience on commodity HMDs and other immersive platforms is both a technical and a design challenge.

We used MiddleVR to mitigate the technical challenges of cross-platform VR applications. There are several important design considerations when developing cross platform VR applications however. It is essential to provide a consistent experience so that users are not confused when moving between platforms. Users should not require more than a trivial amount of training when moving between platforms, otherwise the effectiveness of moving between IVEs is compromised. For this reason, we sought to create spatial interactions that are intuitive and support working with our complex 3D datasets across different platforms.

## 8. CONCLUSION AND FUTURE WORK

Our efforts in this work were focused on three goals. The first was the design of an analytical method for performing static connectivity analysis as a proxy for numerical simulation. The second was the creation of an application that would help reservoir engineers perform well optimization tasks more

effectively using this method. The third was to design this application to take advantage of the benefits of immersive environments. We performed interviews with six reservoir engineering subject matter experts to gather feedback regarding our method and application. Also, we demonstrated the application using three different immersive environments in order to explore the impressions of the reservoir engineering subject matter experts and gather the perceived benefits and drawbacks of each of the environments when it comes to performing well trajectory analyses.

We have presented the results and a discussion of our findings from the interviews. Even though this was an exploratory study, it has advanced our understanding of the needs and expectations of this tool, as well as how immersive environments may benefit reservoir engineers. We plan to improve the capabilities of our application using the suggestions provided by our participants. In the longer term, we plan to proceed with a larger task-oriented user evaluation and have interviews with a larger number of subject matter experts. We hope that our work will provide benefit for those designing immersive applications both in petroleum engineering and in other domains. Furthermore, we hope that our work elucidates how powerful and valid immersive environments are, and highlights their potential to transform the way we explore scientific data.

## 9. ACKNOWLEDGMENTS

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