SIMULATION OF THE CONCEPTUAL DESIGN OF OFFSHORE SALT CAVES FOR CO_2 STORAGE

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KEYWORDS

Carbon capture and storage, Offshore Salt Cave, Systems Engineering, Web-based Simulation, Virtual Prototype.

ABSTRACT

There is a growing demand for systems to store the excess gas produced by the offshore industry, especially gases rich in CO_2. The geological composition of the Santos Basin in Brazil and the location of the production platforms make it plausible to build caves in the salt layer for this purpose. A system engineering model based on Epoch-Era analyses was employed to analyze the possible solutions to the problem aiming at the conceptual design stage. The system was decomposed and described in means of its several components and subsystems. Some of the most important decisions to be made have been outlined. An estimate of the utility and costs involved was obtained for each epoch. The utility was calculated based on the attributes of each solution and the relevance of each attribute to the stakeholders. An analysis of the solutions tradespace was carried out from the utility and cost estimates to discuss the best alternatives. Also, a three-dimensional web-based simulation model was implemented to provide a more realistic picture of the system's operation.

INTRODUCTION

Oil and gas production in the pre-salt region in the Santos basin is of strategic importance for the development of the Brazilian economy in the coming years. This oil produced in pre-salt has a very high gas-oil-ratio (GOR). While a portion of this gas is treated in the plant and can be used for consumption, another fraction needs to be reinjected into the production well (ANP, 2019) or stored in another location.

Gas storage is a critical problem because a huge volume is required to allocate high production levels. Another problem is that storage sites do not always have robust structures that allow high gas pressurization, further limiting the amount that can be stored

A possible solution to this problem is the construction of underground reservoirs for gas storage and disposal, especially gas highly contaminated with CO_2, considered polluting and not economically attractive (Costa et al., 2019a).

The works of McCall et al. (2004) and McCall et al. (2005) discuss the potential to use salt layers below the ocean bed for CO_2 storage. The works of Shi et al. (2017) and Londe (2017) present various alternatives and discuss the powders and cons of each one given the technical, economic, environmental, and safety aspects.

A plausible option, specifically for the Brazilian scenario, is the construction of caves in the saline layer located just above the oil-producing fields (Costa et al., 2017).

The innovative project can be achieved by employing modifications in the existing well construction engineering processes and using adaptations in the construction processes of onshore salt caves.

This work presents the modeling of a cave to store the excess of produced gas, using the point of view of systems engineering with a focus on facilitating decision-making in the early stages of the project.

SALT CAVE MODELING

A complete description of the salt-cave system considered in the present work can be found in Costa *et al.* (2019b). A schematic arrangement of the proposed cave for the storage of gas in the salt layer is presented in Figure 1 to illustrate the main components of this system.

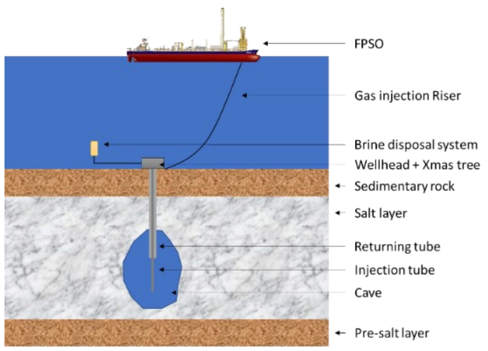

Figure 1: Schematic Arrangement of the Salt-Cave for CO_2 Storage (not in scale; Costa *et al.* 2019b)

The salt cave can be described as a complex system composed of several subsystems that, in turn, have

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several components that throughout the project need to be defined and designed. The approach of systems engineering in maritime systems gaining momentum in the last decade (Gaspar *et al.* 2012ab) and seeks to understand how these components work together by hierarchically categorizing the elements.

Exemplifying, the design of a salt cave requires the joint work of various areas of knowledge such as:

- Well construction engineering
- Submarine systems engineering
- Geomechanical study
- Naval systems and operations
- Flow assurance
- Environmental impact
- Logistics

For an integrated analysis of the system, the procedure presented in Figure 2.

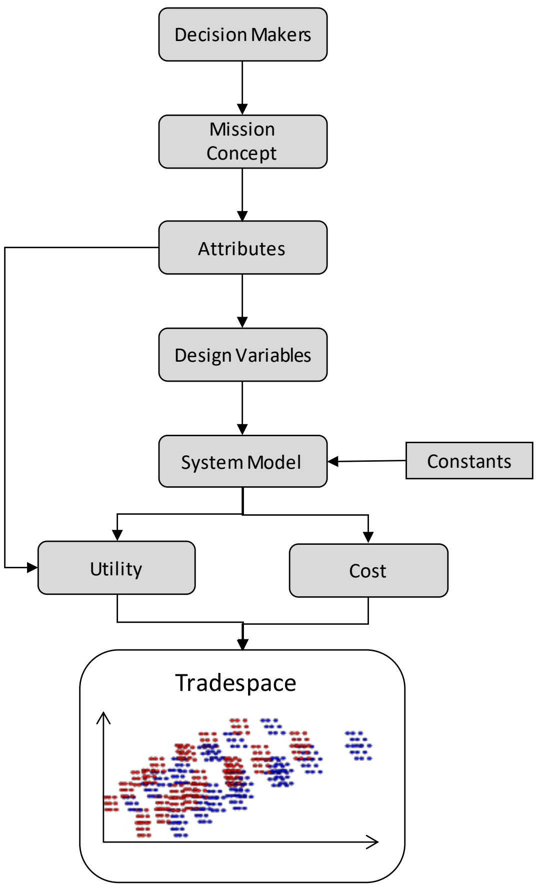


Figure 2: Tradespace Evaluation: Information flow for modeling cost and utility. Adapted from: Ross and Rhodes (2008).

Initially, only the company that has an interest in storing excessive gas will be considered as a stakeholder in the "Decision Makers" block. However, future work may consider multiple stakeholders. Thus, it is possible to state the mission of the concept:

"*Build a cave in the salt layer capable of storing excessive gas production, meeting current legal and environmental requirements.*"

According to this statement, it is possible to define the system attributes, i.e., the items in which the system will be evaluated. In this way, stakeholders can assess the system's ability to deliver the expected value.

The system attributes were chosen as:

- Flowrate capacity
- Volume capacity
- Environmental Impact
- Safety

Design Variables

Design variables are related to the decisions that define or constrain how the system works and, therefore, its capabilities. Based on the mission statement, it is possible to divide the system life cycle into 4 phases:

1. Well Drilling
2. Construction (Dissolution)
3. Operation
4. Abandonment

The drilling stages comprise the wellhead installation, the well drilling and cementing, Christmas tree installation, and the brine disposal system installation. Their requirements generally define this equipment, so we can identify as essential design variables the nominal values of *diameter* and *pressure* under which the system should operate. An additional

The *driller ship* is the most critical equipment in the drilling stage. The well construction quality and safety are directly related to the capabilities and experience of the company hired to perform the task. These factors have been summarized here as three levels of driller operability, which is linked to the number of days necessary to finish the drilling stage, and consequently, related to the cost of the construction operation.

The dissolution stage comprises two possible solutions for the *dissolution system*: using a dedicated unit (DU) or using the FPSO (Floating Production, Storage, and Offloading) platform available infrastructure.

When using a dedicated unit, a subsea pump will provide water to the cave dissolution. This subsea pump requires an infrastructure consisting of a generator, an umbilical cable to provide high voltage electricity, a water intake pipe, and connection equipment as flowlines, terminals, and jumpers.

The solution using the FPSO structure requires a dry pump located in topside, a suspended riser for water intake, a riser to water injection. For simplicity, at this moment, we can assume that the FPSO power generation module can provide the electricity to the dry pump.

Independent from the dissolution system, after the water pass through the Xmas tree, wellhead, and injection pipe, it will be mixed with dissolved salt. The brine will return to well through the annulus pipe, and it may require a second submerged pump to provide the flowrate until the diffuser located in sea depth with enough current to facilitate the brine dissolution in the seawater.

After defining the equipment set, it is necessary to determine the *dissolution flowrate* and the *dissolution time*, which will result in the cave size.

Once the cave has the desired dimensions, it is necessary to carry out the preparations for the operation phase. In the case of the DU solution, this consists of performing the entire installation of the injection system in the FPSO. In the case of the FPSO solution, it is necessary to disconnect the riser from the water injection system and connect it to the gas production line.

The operating stage consists of all the time when the FPSO will be replacing brine with the gas that will be stored. At this stage, it is necessary to monitor the pressures and structural integrity of the cave and constant care with the discharge of brine into the seabed.

Finally, we have the abandonment phase in which the wellhead is sealed, and all injection equipment is removed. For this phase, it is necessary to ensure the structural stability of the cave and monitoring and safety systems.

Despite the system's various phases, most project decisions are concentrated in phases 1 and 2. In this way, for conceptual design, no additional variable needs to be adopted for phases 3 and 4. Thus, the salt-cave design variables and the parameters used to generate the different solutions are presented in Table 1, which also shows the range and steps of the assumed values.

Table 1: Salt Cave Conceptual Design Variables

Design Variables	Unit	Range	Steps
Selection of Driller	Operability	90% – 99%	3
Nominal Diameter	in	3 – 7	3
Nominal Pressure	ksi	5 – 15	3
Dissolution System	type	DU / FPSO	2
Dissolution Flowrate	m³/h	500 – 780	3
Dissolution Time	days	730 – 1095	3

In addition to the design variables, it is necessary to provide the model with the values of some constants. The choice of which parameters to keep constant or variable depends mainly on the designer's experience. However, in the early stages of design, an extensive set of variables can result in long processing time and hinder the process of obtaining insights about the system.

The salt-cave model constants mainly concern in some factors such as cave and FPSO relative location, depth, a vertical dimension of the salt layer in relation to the ocean bed. In this work, all these things were defined *a priori*. However, choosing the best location to build the cave could be one of the system's variables, for example.

Also, there are some classes of operations and equipment that are always the same, regardless of the solution. For example, all alternatives must pass through the same safety and integrity tests.

System Utility

The system can be assessed by defining a single value that expresses the stakeholder satisfaction. This value is generally defined as the system utility, a value usually taken between 0 and 1, where 0 represents a system that does not deliver value to its user, and 1 represents a system that delivers the highest possible value.

The utility can be determined by evaluating each of the system attributes and using aggregation functions, as presented, for example, in Keeney and Raiffa (1993). This methodology is the so-called Multi-Attribute Tradespace Exploration (MATE).

Each attribute depends on a subset of the Design Variables. For example, the evaluation of Flowrate capacity depends on the Nominal Diameter and the Nominal pressure. Then, for each attribute value X_k will have an associated single-attribute utility function U_k as presented in Figure 3.

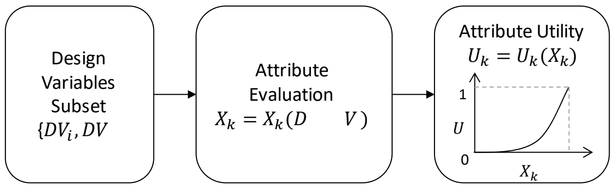


Figure 3: Attribute Utility Evaluation

The multi-attribute utility U is obtained by performing a weighted sum of the attribute's utilities, as shown in Eq. (1):

$$U = \sum_{k=1}^{N} w_k \cdot U_k(X_k) \qquad (1)$$

in which N is the number of evaluated attributes, w_k are the weights defined by stakeholder preferences and by Eq. (2):

$$\sum_{k=1}^{N} w_k = 1 \qquad (2)$$

In present work, it was considered that all four attributes have the same weights $w_k = 0.25$.

Table 2 presents the dependency between the attributes and design variables considered in the present work.

Table 2: Design Variables and Attributes Dependency

Design Variable	Attributes			
	Flowrate capacity	Volume Capacity	Environ-mental Impact	Safety
Driller				x
Nominal Diameter	x			
Nominal Pressure	x			x
Dissolution System			x	x
Dissolution Flowrate		x	x	x
Dissolution Time		x	x	

System Costs

In addition to calculating the utility, it is necessary to perform an initial estimative of the involved costs for each of the generated solutions. This estimative is just for decision-making purposes, not for budget planning. The most important point is the relative costs of various concepts. The methodology adopted is that presented in Bai and Bai (2018), which consists in to obtain the basic cost of an equipment C_0 and multiply by cost-driving factors f_i. A correction cost C_{corr} can also be applied, as shown in Eq. (3):

$$C_{eq} = C_0 \cdot f_1 \cdot f_2 \cdot f_3 \cdot ... + C_{corr} \qquad (3)$$

The cost-driving factors can be specified, for example, as equipment type, pressure, bore size, or any other characteristic that impacts on equipment price.

Other costs, such as Drill Ship, Platform Supply Vessel (PSV), Offshore Supply Vessel (OSV), Pipe Laying Supply Vessel (PLSV) chartering, or consumable utilization, has been considered according to the average market price and the amount or the time required for each solution.

Besides, the costs can be divided into capital expenditure (CAPEX) and operational expenditure (OPEX) to provide a broader analysis scenario.

For reasons of confidentiality of information, the costs will be presented in a nondimensional way where 1 represents the solution with the highest cost.

The list of materials and equipment used for the cost estimate is shown in Table 3. Some items in this list are just used depending on the solution adopted for dissolution (DU or FPSO).

Table 3: Material and Equipment Considered for Cost Estimation

Drilling phase	Dissolution phase
Casing and tubing	*Lines*
▪ External Casing	▪ Umbilical
▪ Intermediary Casing	▪ Riser
▪ Internal Casing	▪ Flowline
▪ Brine return tubing	▪ Contingency riser
▪ Seawater injection tubing	▪ Contingency flowline
Consumables	▪ Brine disposal riser
▪ Drilling fluid	*PSV*
▪ Cement	▪ PSV subsea pump installation
Drill Ship	▪ PLSV
▪ Drilling, casing, tubing, and integrity tests	▪ Mechanical integrity test
▪ Offshore support vessel	▪ Monitoring
▪ Service companies	*Equipment*
Equipment	▪ Subsea pump (water)
▪ Wellhead	▪ Subsea pump (brine)
▪ Christmas Tree	▪ Power Module
	▪ Diffusers

Tradespace Exploration

The modeling presented in previous sections shown how to determine the stakeholder needs and convert in values. Then, it is possible to perform a tradespace exploration to examine the performance of systems and to verify the relationship between each proposed solution, which helps to better understand the problems related to the key decisions in early design stages.

The results presented in Figure 4 were obtained by applying the utility and costs model to the solutions generated from the combination of the project variables previously shown in Table 1.

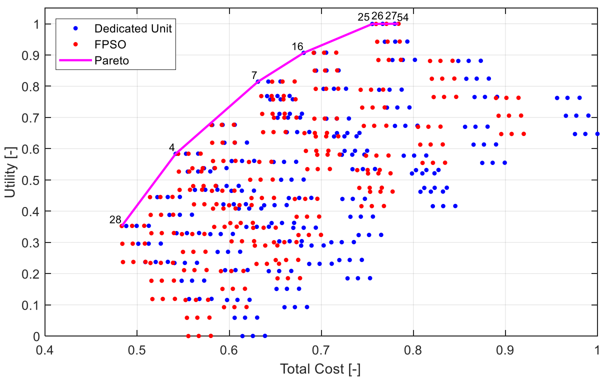


Figure 4: Utility vs. Total Cost for each Generated Solution

In this figure, each point represents a solution; points in blue represent the solutions using a DU, and points in red represent the solutions using the FPSO resources for dissolution. The magenta curve is the Pareto boundary of the simulated cases.

For this simulation, were generated 486 solutions. The number near the Pareto boundary is the ID of the eight designs contained in the Pareto boundary. These solutions are described in Table 4.

Table 4: Description of Solutions Contained in the Pareto Boundary

ID	Utility [-]	Cost [-]	Driller Oper. [%]	Diam [in]	Press (ksi)	Diss. Sys. [-]	Diss. Flow [m³/h]	Diss. Time [days]
4	0.58	0.54	90%	5	5	'DU'	500	730
7	0.81	0.63	90%	7	5	'DU'	500	730
16	0.91	0.68	90%	7	10	'DU'	500	730
25	1.00	0.76	90%	7	15	'DU'	500	730
26	1.00	0.77	95%	7	15	'DU'	500	730
27	1.00	0.78	99%	7	15	'DU'	500	730
28	0.35	0.48	90%	3	5	'FPSO'	500	730
54	1.00	0.78	99%	7	15	'FPSO'	500	730

Essential considerations can be made from the Pareto solutions. First, all solutions presented *Dissolution Flowrate* of 500 m^3/h and *Dissolution Time* of 730 days. Both values are the minimum inputs and have a very high impact on system costs. These values will result in caves with less storage capacity, but in the balance of attributes, they are the most efficient.

Six of the eight Pareto solutions consider the *Nominal Diameter* of 7 in. The only change between solutions 4 and 7 is the nominal diameter, which has a small impact on costs (from 0.54 to 0.63) but has a significant influence on utility (from 0.58 to 0.81).

Another interesting comparison is between solutions 27 and 54. The only difference, in this case, is the adopted *Dissolution System*. These solutions deliver practically the same value to the stakeholders (the non-dimensional cost is different just in the third decimal place), which shows that for some parameter combinations, one or another variable may no longer be necessary. In a second step, it is possible to reduce the design variable vector, for example.

WEB-BASED VISUALIZATION

Three-dimensional visualization tools in a virtual environment are essential to the design and development of innovative projects. In possession of these tools, the designers can inform and present the concepts clearly and objectively elucidating many doubts of stakeholders.

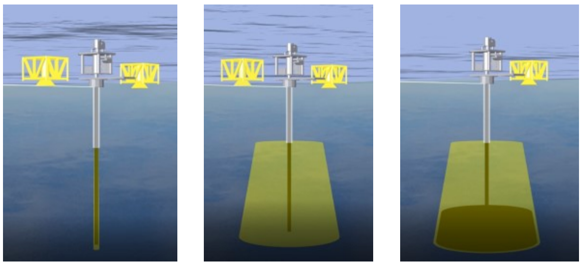
The three-dimensional salt cave model was implemented on the Vesseljs library (Gaspar, 2018), which is an open-source JavaScript library to perform the visualization of complex marine engineering systems. Fonseca and Gaspar (2019) present several advantages in using this kind of collaborative platform, as well as offers some examples and functionalities that are already implemented. One of the benefits of using Vesseljs consists of the fact it is a web-based library compatible with the most common web browser, making unnecessary the necessity for further software installation and increasing its scalability.

As Vesseljs is a platform with continuous development, some new features were implemented to model the salt cave system environment: for instance, the classes for representing the lines and the series of stereolithography (STL) 3D models of the ships and equipment. An auxiliary snippet code was also generated to calculate the position and geometry of the elements throughout the time. In this first implementation, the model has the sole purpose of visualizing the solutions generated by the systems engineering model.

A screenshot of the model is presented in Figure 5, in which it is possible to visualize the equipment involved in the operation, such as submerged pumps, wellhead, and Christmas tree. The arrangement of the well pipes and the dissolution process generating the cave shape was modeled as predicted in Costa et al. (2019b). It is also possible to observe the floating units as well as the umbilical cables and catenary risers.

Figure 5: Screenshot of the Salt Cave Visualization Module Implemented in the VesselJs Platform. Available in http://vesseljs.org

In the control panel is possible to set the flux dissolution rate and time parameters as shown in Table 1, the flow rate of carbon dioxide to the cave, the control button to start, pause or restart the simulation as well as observe the elapsed time. Figure 6 presents a sequence of three different stages of simulation: (a) the beginning of dissolution when the well is drilled, the subsea equipment is installed, and the submerged pump is ready to inject water to dissolve the cave; (b) represents the dissolved cave stage when the desired dimensions were obtained, and the cave is fulfilled with brine; (c) represents the process of substituting the brine by the FPSO gas when the equipment used to the dissolution process was removed, and the gas is filling the cave.



(a) (b) (c)

Figure 6: Sequence of Different Stages of Cave Operation: (a) Beginning of Dissolution, (b) Dissolution completed, (c) CO_2 Storage

Although the web-visualization tool itself is not a new implementation, it is the first time it has been applied to the study of complex systems involving concomitantly floating systems, subsea systems, well engineering, and geomechanical systems. The tool application potential can be extended beyond simple visualization, considering a platform for centralization and integration of the areas involved.

From the model parameterization, it is possible to connect to the various databases of hydrodynamic modeling, geotechnics, flow assurance, and obtain a broad model of cave construction and operation.

CONCLUSIONS AND FUTURE WORK

A system engineering model was presented in order to provide insights into decisions making in the early stages of the conceptual design of an offshore salt cave system for CO_2 storage.

The multi-attribute tradespace exploration (MATE) methodology was employed to obtain the utility and costs estimates for a set of possible solutions. Although simplified, the model was able to raise some interesting points and trends about the design of the salt cave system.

The obtained pareto boundary describes two distinct classes of solutions: small caves with a low cost and large caves with a higher cost.

For a more in-depth analysis, future work is intended to complement the model considering the temporal, contextual, and perceptual aspects as proposed by Rhodes and Ross (2010).

Regarding the visualization model, we corroborate in this paper with the call open and collaborative visualization methods made by Gaspar (2018), in his consideration for developing future engineering analysis and simulation in JavaScript (JS). The examples here presented are working in the process, and much of the library structure and methods intend to be improved as the research develops. The main point defended in this example is that technology is not a bottleneck for collaborative design and simulation of offshore systems, neither the speed of the computer processors and memory size, but rather how efficient maritime simulation and design data is able to be transferred from books and experience to useful reusable models.

Further work could involve not only the demonstration of its components but the mathematical simulation response of the equipment, such as internal pressure in the epoch and pipes. The visualization could have its applicability expanded by incorporating the costs and utility calculations produced in this article.

Furthermore, web-based platforms already had a good response for visualizing data collected in a scale model, as mentioned in Fonseca and Gaspar (2020). In future work, the model could be used as a digital twin of the real operation for monitoring the equipment and for validation of the methodology used.

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