ORIGINAL ARTICLE

Leveraging Epoch-Era Analysis and Digital Twin for Effective System Concept and Execution: A CO_2 Storage Salt-Cave Project

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With the demand to reduce the release of CO_2-rich gases into the atmosphere, the offshore industry is turning to systems for gas capture and storage. The construction of a cave for that purpose is planned in the salt layer of the Santos Basin, Brazil; however, numerous factors bring uncertainties to the project. We propose combining systems engineering methods and digital twin technology to enable system concept and execution aiming at value robustness. The system is modeled in mission, subsystems, components, and design attributes. System utilities and costs are estimated for a range of viable solutions based on the relevance of each attribute to the stakeholders. The alternatives are evaluated using the Epoch-Era Analysis framework for analyzing the system's performance over time in changing future scenarios. The system model also outlines a digital twin concept and identifies how it might support salt cave design and operations. Finally, the potential of tuning and improving system evaluation based on gathered data is examined, and measures toward further digital twin development are recommended.

KEYWORDS
carbon capture and storage, salt-cave, epoch-era analysis, pre-salt layer, digital twin, digitalization

1 | INTRODUCTION

1.1 | Offshore Carbon Capture and Storage

The present text intends to approach the development of the initial phases of an offshore carbon capture and storage project from the perspective of Systems Engineering. Nevertheless, the work proposes using the modeling described here in conjunction with modern digitization tools, more precisely, the digital twins. Thus, this introduction is divided into three parts which address a literature review on offshore Carbon Capture and Storage (CCS), a description of the methodology adopted for the systems engineering approach, and the role of digital twins in the design and simulation of complex systems.

Despite significant efforts to develop renewable alternatives, the world's energy matrix is still heavily dependent on fossil fuels. According to Schrag (2009), it will be vital to implement effective measures to capture CO_2 from primary sources and store it in geological reservoirs to deal with climate impacts. However, offshore reservoirs have received little attention despite having advantages over onshore reservoirs. Some studies were developed to discuss these advantages and describe the possibilities in this context. Sweatman et al. (2011) presents an overview of current technologies, listing and describing the main commercial projects of offshore CCS. Cavanagh and Ringrose (2014) presents the advantages of using carbon dioxide for injection into oil wells, thereby extending oil recovery in a process called Enhanced Oil Recovery (EOR).

Fernandez et al. (2016) and Blackford et al. (2020) present an analysis of how to consider the uncertainty in reservoir properties in conjunction with the variation of CO_2 flow to estimate the impacts on risk assessment of the CCS system. The works of Dean et al. (2020) and Esposito et al. (2021) raise several points to reduce the cost of monitoring technologies and expand the automation of data processing and analysis that will be of utmost importance to support the safe and efficient deployment of large-scale offshore CCS. Furthermore, Ozaki et al. (2013), in turn, discusses the crucial issue of CO_2 transport in the CCS operating chain by assessing the feasibility of using vessels dedicated to this type of gas.

Offshore oil production on the Brazilian coast in the pre-salt reservoirs at Santos Basin has been significantly associated with natural gas production. A portion of this gas is treated on the platform removing the CO_2 excess, and can be used for consumption. There are at least two viable alternatives to the surplus gas with high CO_2 concentration: reinject the gas in the production field or store this gas in another location. The reinjection is not always viable because it can, for example, increase the CO_2 proportion in the produced gas. According to data from the ANP (2019), Brazil's natural gas production in 2018 was 40 billion m^3, being 79% associated and 21% non-associated gas. Of these, 12 billion m^3 were reinjected, and 1.3 billion m^3 were burned or lost.

Beck et al. (2011) and Iglesias et al. (2015) summarize the current scenario of CCS projects in Brazil. The work highlights carbon capture and its geological storage with the potential to implement CCS directly in offshore production units. However, constructing a reservoir can solve the problem when no geological reservoirs are available or close to the storage location.

The work of Costa et al. (2017) proposes the construction of "giant" caves in the salt layer of the ocean bed to store the large amount of gas produced in the area. The works of McCall et al. (2004), McCall et al. (2005), and Costa et al. (2019b) discuss the potential to use salt layers below the ocean bed for CO_2 storage. The works of Shi et al. (2017) and Londe et al. (2017) present various alternatives and discuss the pros and cons of each one, given the technical, economic, environmental, and safety aspects.

1.2 | Epoch-Era Analysis Applied to Maritime Systems

A traditional system design approach optimizes the system against a set of objectives defined for a given context. Although accepted for short-term decisions, this approach is insufficient when designing strategies that aim to provide value to stakeholders in the long term in the face of a rapidly changing scenario. Rhodes and Ross (2010) propose that in addition to the traditional aspects of the system's design (Structural and Behavioral), other equally important aspects (Contextual, Temporal, and Perceptual) must be taken into account.

According to Ross et al. (2008), value robustness is precisely the system's capacity to deliver value continuously in constantly changing contexts. Systems must be designed using timescales, each with its context, to achieve this value robustness, providing a broader overview of the associated risks and gains. Thus, it is possible to mention the "Epoch-Era Analysis" (EEA), presented in work by Ross and Rhodes (2008c), which provides a structured and rational framework for analyzing the system's adaptation over time.

An "Epoch" is a specific time period that has a fixed context and needs. The constraints, design concepts, available technology, and expectations are all constant within an Epoch. However, in the event of significant changes to any of these factors, a new Epoch is adopted to reflect the new context accurately. The collection of successive Epochs throughout the lifespan of a system is referred to as an "Era". A stepwise process to detail the whole process of epoch-era construction in the maritime sector is presented by Gaspar et al. (2012a)"

In the works of McManus and Hastings (2006) and Valerdi et al. (2007), a framework is presented to help understand uncertainties in the design of systems, techniques to mitigate these uncertainties, and even take advantage of them. Research by Ross and Rhodes (2008a) seeks to understand the effectiveness of systems engineering in modern companies by developing new empirical knowledge related to systemic thinking and engineering practice. Ross and Rhodes (2008b) present a method for estimating, in the conceptual phases, the latent value of the project throughout its life. Ross et al. (2008) explain how the system's design should consider the changes inherent to time and how designers should use this in decision-making. In addition to these, one can mention the examples and applications obtained in Richards et al. (2008), Rhodes et al. (2009), and Roberts et al. (2009).

The EEA methodology has already been successfully employed in studying complex marine and ocean systems. Such systems are commonly designed to operate for approximately 20 to 30 years, making the temporal aspect one factor that adds complexity. In this sense, Gaspar et al. (2012a) propose modeling time uncertainties using the "Epochs" to describe the possible market changes and evaluate the pros and cons of each attribute. The long-term evaluation combines several "Epochs" in an "Era." Complementary, Gaspar et al. (2012b) present a more general discussion on the complex aspects present in the design of vessels and proposes the use of the RSC (Responsive Systems Comparison) method proposed in Ross and Rhodes (2008a).

The works of Keane et al. (2015) and Pettersen and Erikstad (2017) present two examples of EEA applications in the conceptual design of OSVs (Offshore Construction Vessels) ships. These works mainly discuss the need to understand and outline a complete panorama of the scenario in which the system is inserted so that the results obtained outcome in a system capable of delivering value over time in a complex, uncertain, and constantly changing context. The EEA adoption proved flexible enough to make the necessary decisions to ensure flexibility and competitiveness in the vessel operation.

Rehn et al. (2018) present a study on ocean systems flexibility in which the ability of the system to meet various needs is studied as a function of its form change capability. The concepts of flexibility in systems design are presented more generally and in-depth in De Neufville and Scholtes (2011). Their definitions are fundamental to formulating and analyzing the various means of maximizing the system's value. In this context, it is possible to mention that the EEA methodology provides a structured and rational method of analyzing the system's adaptation over time. It can be applied in the present study to evaluate the complexity of the subsea systems necessary for offshore CCS operation.

1.3 | A Digital Twin Approach to Design and Simulation of Complex Systems

The digital twin originated in the aerospace sector as a proposal to centralize all data, models, and simulations for a given system to support its operation and maintenance Shafto et al. (2010). Since then, the concept has gained increasing interest and spread through various industrial sectors. The digitalization process of making virtual copies of machines or systems is revolutionizing the industry in general (Tao and Qi, 2019). According to Qi et al. (2021), the virtual model highly depends on the quality and quantity of the measurements performed in the physical system. The information collected must be recognized and translated into the real world. In contrast, the system must be designed to receive control commands based on the predictions and estimates of its virtual counterpart.

The digital twin is also gaining interest in the oil and gas sector. While there have previously localized solutions for well monitoring and control, recent advances in cloud architecture, industrial internet of things, data analytics, and machine learning are enablers of full digital twins. It is now expected that it will be possible to realize comprehensive hubs aggregating all digital aspects of well construction and exploration within the following decades (Feder, 2021). DNV-GL (2021) pointed out that the digital twins are among the top ten digitalization investment priorities in the oil and gas industry.

Cameron et al. (2018) defend that oil and gas digitalization must comprehend the asset in combination with its lifecycle (concept, engineering, construction, operations, and decommissioning). They mention that many efforts were made for specific disciplines, like monitoring drilling fluids or flow assurance in this particular industry. However, new developments must comprise a more comprehensive and interdisciplinary twin.

Previous works have investigated different aspects of digital twin development. Rebentisch et al. (2021) stated the necessity to conceive, operate and evaluate a digital twin as part of the sociotechnical system inside which it is operated, as opposed to an isolated digitalization project. Thus, the development of marine and ocean digital twins, including offshore CCS digital twins, will have a greater chance of success if designed from the beginning in conjunction with the broader system. The quality and usefulness of DT will depend on an integrated design with monitoring and control definitions, adding even more complexity in the scope of system engineering.

Fonseca and Gaspar (2020) gave an overview of the challenges to implementing a cohesive DT in the maritime domain, including those related to services, networks, and software. The work emphasizes the need to continue developing and adopting data modeling standards to enable interoperability and data exchange among stakeholders in the maritime value chain. This will allow systematic share the system definition and sensor data contained in the digital twin by digital services and simulation models.

Later work presented a standards-based digital twin of an experiment with a scale model ship as a prototype for developing digital twin ships (Fonseca et al., 2022). It proposed combining existing standards for 3D visualization, sensor logs, and ship taxonomy to model digital twins with intelligible data content following documented conventions. Still, it allowed stakeholders to choose the taxonomies and data storage strategies that better suit their necessities.

Concluding this introduction, this work proposes two main contributions to the Systems Engineering literature: the discussion on applying an SE methodology to the CCS theme and the discussion about the possibilities of joint use of an SE framework with a digital twin. These topics will be described in detail in the following sections.

2 | SYSTEM MODELLING OF A SALT CAVE FOR CO_2 STORAGE

2.1 | Modelling and Analysis of Salt Cave as a Complex System

The construction and operation of caves in the salt layer constitute a great technical-scientific challenge. Each phase has a high degree of process complexity to ensure the concept's success. The offshore CCS arrangement is similar to an oil and gas system, consisting of floating units, risers and pipelines, subsea equipment, wells, and reservoirs. That is, a complex, multidisciplinary system composed of several levels of subsystems. Several areas of knowledge are interconnected, such as geomechanics, well drilling, submarine systems, naval systems and operations, logistics, risk analysis, environmental impact, and flow assurance.

As discussed by Goulart et al. (2020), most of the technologies necessary for the practical construction of a salt cave are in the development stages. Much can be taken advantage of in the offshore industry, such as drilling technologies, operation, monitoring deepwater wells, and operating technologies for subsea equipment. However, some essential items need to be adapted or developed, such as adapting Christmas trees and wellheads and the determination of new technical specifications for the casing set and cementing process to avoid the leakage of gases at high pressures.

A step is to perform a system hierarchization to visualize and handle its intrinsic complexity. This process consists of describing the subsystems and equipment belonging to the system and also understanding the role of the salt cave project in the context of the oil and gas industry.

The center pane on Fig. 1 presents the salt cave as a system with equipment for CO_2 storage and is connected to an external unit, such as an FPSO, which produces and injects the gas into the cave as a by-product of oil and gas exploration. The panes to the left illustrate the salt cave system's decomposition into subsystems and components. These are used to identify the cave's design variables, map them to the desired system attributes, and estimate involved capital costs. The panes to the right depict the salt cave as part of broader multi-cave systems and of the oil and gas production chain. These views are later used to evaluate the salt cave utilities, as perceived by its stakeholders, in different contexts imposed by these overarching systems.

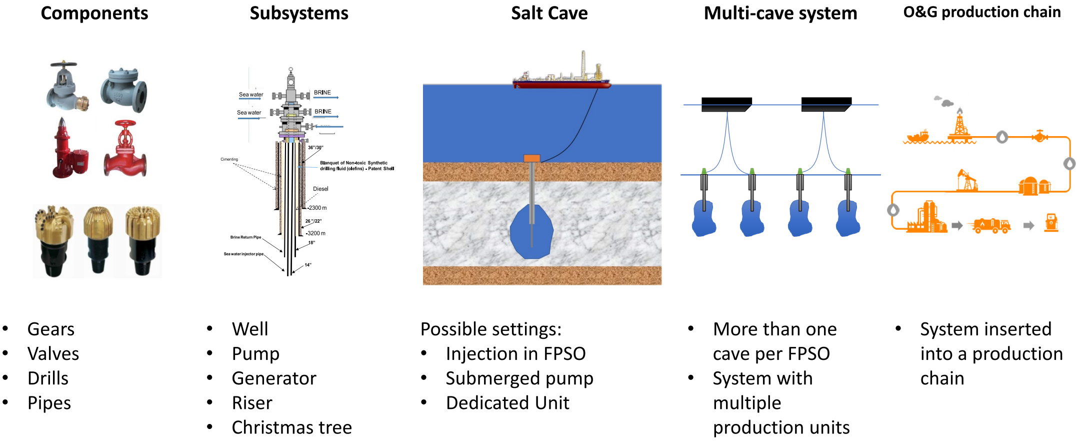


FIGURE 1 Salt cave as a complex system. Encapsulation from left to right, decomposition in the opposite direction.

Yasseri (2014) points out that systems engineering methodologies are feasible tools for dealing with such complexity. The EEA allows for identifying system utility and assessing value robustness during system concept, thus being a suitable tool. Applying the EEA method to the salt cave problem lies in identifying the critical design parameters and modeling utility and cost estimation for the possible system variations. All the inherent complexity of a specific solution must be expressed by these two parameters plotted as a tradespace, effectively providing a comparative basis for evaluating project uncertainties. Generally, a tradespace can be defined using a 2D graphical presentation of utility versus costs. The idea is to obtain a frontier in which the increase in utility necessarily increases the cost of the solution, or the decrease of the expenses implies a reduction in the system's utility, i.e., a Pareto frontier. As shown in the following sections, in the adopted methodology, one evaluation step consists in obtaining a tradespace for a given context. By context, we mean exogenous factors that influence the perception of utility or impact the costs of a solution—for example, political factors, development of new technologies, or changing global demands. So, different tradespaces can be obtained for different contexts.

Figure 2 presents an overview of the dataflow needed for the performed analyses and the text sections in which each is presented and described. As explained in previous paragraphs, this Section 2 focuses on the detailed description of the necessary assumptions for modeling the system. Section 2.2 identifies system stakeholders and mission. Once the attributes are defined as presented in Section 2.3, it is important to identify the set of variables capable of describing the system, presented in Section 2.4. The system's utility is evaluated in Section 3.1, and the estimative of costs is presented in Section 3.2. The "Multi-Epoch Analysis" and "Era Analysis" applications are presented in Sections 3.3 and 3.4, respectively. The main goal is to design a system that continuously delivers value to stakeholders over time in scenarios with changing contexts and needs (Ross and Rhodes, 2008a).

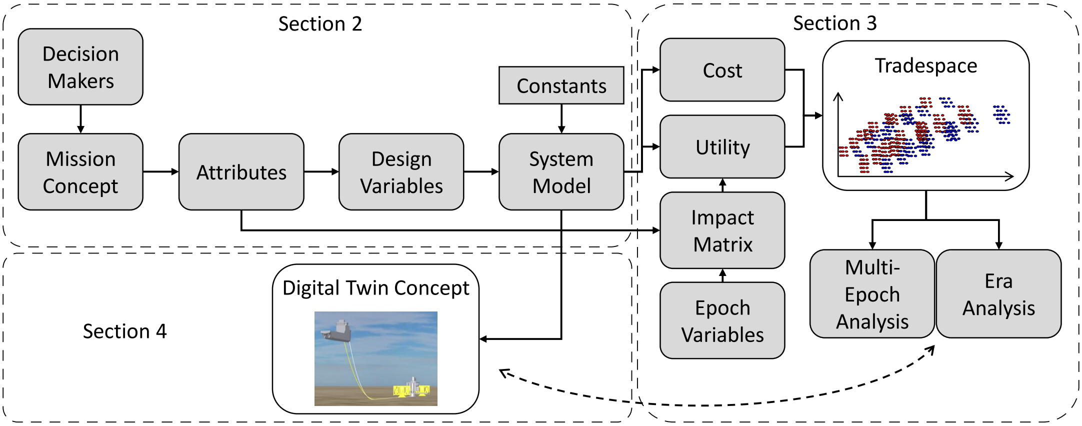


FIGURE 2 Flowchart of the methods and analyses employed in the present work depicting in which section it is detailed.

In addition, Section 4 proposes a digital twin implementation as a preliminary investigation of applying data-based methods to assist salt cave design and operation and eventually reduce modeling uncertainties associated with its lifecycle as a complex, innovative system. Section 4.1 details the rationales of leveraging the exact system model used for EEA to inform a digital twin specification for the offshore CCS system. Section 4.2 explains the digital twin as a tool for salt cave virtual prototyping during early-stage design, providing an example with a web-based application. Section 4.3 continues by explaining the digital twin's role in supporting salt cave dissolution and operation stages with monitoring and control functionalities. Section 4.4 examines the potential of using data gathered through the lifecycle to evaluate and refine the EEA models, thus increasing the trustworthiness of their performance estimates.

The presented digital twin outline is considered exploratory for two reasons. One is the current status of digital twins as an emerging trend, meaning that some of its enabling technologies are not yet mature. Another is that a significant amount of workload is required to define a specification sufficient for developing and deploying a comprehensive digital system, extending beyond this work's scope. Section 4.5 discusses paths and challenges to further development and implementation.

2.2 | Identifying Stakeholders and Mission

Initially, only the company interested in storing excessive gas will be considered 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."

Based on the mission statement, it is possible to divide the system lifecycle into 4 phases:

1. *Well drilling*: a well with two pipes (injection and return) is drilled up to the salt layer; water is injected until the salt around the well dissolves and becomes brine, part of which is removed by the return pipe and appropriately disposed of in the ocean bed.
2. *Construction (dissolution)*: during this process, in addition to the water circulation, interventions are necessary to verify the cave's geometric shape and structural stability.
3. *Operation*: once the cave has the desired dimensions, it starts the operating stage in which the gas production line is connected to the cave, and the brine replacement process begins. The cave's pressure must be within an acceptable range during this process. Also, verification of cave filling is required.
4. *Abandonment*: upon reaching the maximum fill level, the system enters its abandonment stage, where well inlets and outlets must be sealed and spare equipment uninstalled. Monitoring is required to keep the gas in the cave indefinitely.

Figure 3 illustrates phases 2 and 3: (a) is 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.

2.3 | Articulating System Attributes

According to this mission, it is possible to define the system attributes, i.e., the items in which the system will be evaluated. This way, stakeholders can assess the system's ability to deliver the expected value. According to this information, it is possible to define the system's attributes based on the stakeholders' expectations and the project's complexity.

The attributes adopted in this study were obtained after a conversation with professionals from energy companies interested in implementing CCS in their line production. The adopted attributes are:

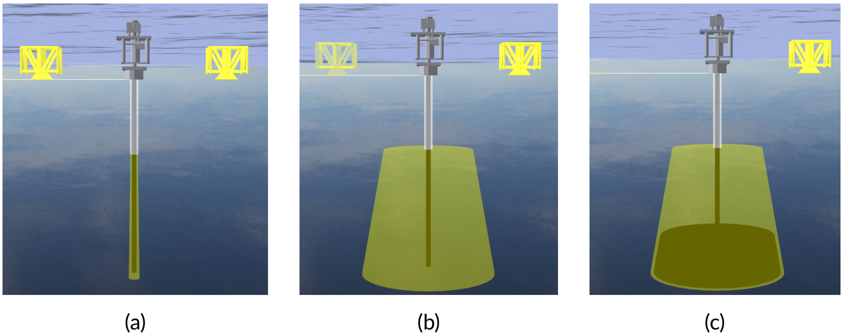

(a) (b) (c)

FIGURE 3 Scheme of salt cave dissolution and operation. From left to right: the beginning of dissolution, dissolution completed, and CO_2 storage.

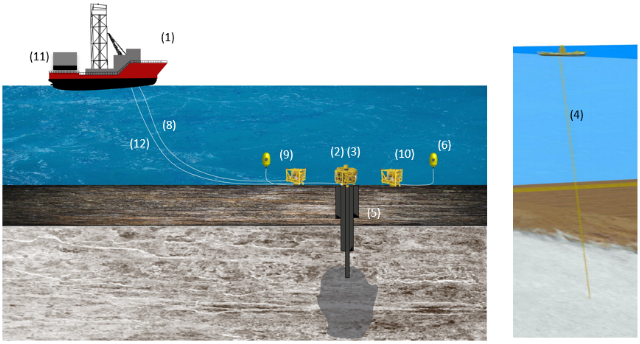
- *Flowrate capacity*: is related to the amount of CO_2 that can be drained from production to the reservoir. The chosen equipment must be accordingly dimensioned so the gas will not be the operation bottleneck.
- *Volume capacity*: is the total amount of CO_2 that can be stored in the reservoir. Regardless of the flow, the reservoir must have a sufficient volume to store the CO_2 produced by the production unit.
- *Environmental impact*: measures the interference the salt cave will cause in the environment. Although beneficial from the point of view of not emitting carbon dioxide, the construction and operation of the cave are not free from the emission of pollutants and other by-products, such as the release of dissolution brine in the ocean.
- *Safety*: an essential factor is that all operations are carried out safely; that is, there are no leaks, landslides, high pressures, loss of equipment, and environmental disasters. Depending on the design variables, each viable solution can be assessed by its degree of security.

2.4 | Identifying Design Variables

Design variables are related to the decisions that define or constrain how the system works and, therefore, its capabilities. It is possible to closely examine the system lifecycle phases to identify how system design parameters and attributes are related (Section 2.2). The drilling stages comprise the wellhead installation, the well drilling and cementing, XT installation, and the brine disposal system installation. Costa et al. (2020) present an example of a possible well configuration. Their requirements generally define this equipment, so we can define as important design variables the nominal values of *diameter* and *pressure* under which the system should operate. The *driller ship* is the most critical equipment in the drilling stage. The well construction quality and safety are 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 linked to the number of days necessary to accomplish the drilling stage and, consequently, related to the cost of the construction operation.

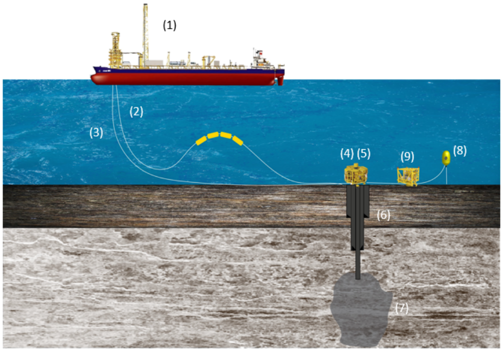
The dissolution stage comprises two possible solutions for the *dissolution system*: using a dedicated unit (DU) or using the FPSO (Floating Production, Storage, and Offloading) available resources. A subsea pump will provide cave dissolution when using a dedicated unit. This subsea pump requires a generator, an umbilical cable to provide high voltage electricity, a water intake pipe, and connection equipment such as flowlines, terminals, and jumpers, as presented in Fig. 4. The FPSO infrastructure solution requires a dry pump on the topside, a suspended riser for water intake, and a riser for water injection, as presented in Fig. 5. For simplicity, at this moment, we can assume that the

FPSO power generation module can provide electricity to the dry pump. A complete description of the salt-cave system considered in the present work can be found in Costa et al. (2019a).



(1)	Dedicated Unit
(2)	Wellhead
(3)	Xmas tree
(4)	Drilling riser
(5)	Well
(6)	Brine Disposal
(7)	Sonar
(8)	Umbilical
(9)	Sub. Pump
(10)	Sub. Pump (brine)
(11)	Energy generator
(12)	Electric cable

FIGURE 4 Schematic arrangement for the dissolution stage using a dedicated unit. Not in scale.



(1)	FPSO
(2)	Injection Riser
(3)	Umbilical
(4)	Xmas tree
(5)	Wellhead
(6)	Well
(7)	Salt cave
(8)	Brine Disposal
(9)	Sub. Pump (brine)

FIGURE 5 Schematic arrangement for the dissolution stage using the FPSO resources. Not in scale.

Independent from the dissolution system, the water will be mixed with dissolved salt after passing through the wellhead and the XT. The brine will return to the well through the annulus pipe. It may require a second submerged pump to provide the flowrate until the diffuser, located at a depth with enough current to facilitate the brine dissolution in the seawater, decreasing the environmental impact.

After defining the equipment set, it is necessary to determine the *dissolution flowrate* and the *dissolution time*. These two parameters together will result in the cave size directly linked to the CO_2 storage capacity. 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 stages, most project decisions are concentrated in phases 1 and 2. In this way, for conceptual design, no additional variable must 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	Values
Selection of Driller Vessel	Operability	90%; 95%; 99%
Nominal Diameter (Bore size)	in	3; 5; 7
Nominal Pressure	ksi	5; 10; 15
Dissolution System	type	DU; FPSO
Dissolution Flowrate	m^3/h	500; 640; 780
Dissolution Time	days	730; 910; 1095
	Number of possible designs:	**486**

The choice and selection of the drilling vessel must consider several factors. Various companies and equipment can be chartered to perform the drilling and completion of the well. The drillers can be ships or semi-submersible platforms that can be moored or have a DP system, and they can be equipped with more robust or straightforward deck equipment. More complex drilling units have a much higher operation availability but a very high charter cost.

In this work, all the factors necessary for the choice of drillers were synthesized by a parameter called "operability." Simpler units have 90% operability, which means that 10% of the time system cannot operate. More complex units have 99% operability. The complexity of the adopted drilling system impacts the cost of operation and safety, for example.

Although specific, the values adopted in the present study were obtained in two different ways: considering the typical industry values considering the detailed studies about salt cave dissolution. According to Bai and Bai (2018), after decades of experience, the subsea industry has standardized equipment around 5 inches for *nominal diameter* and 10 ksi for *nominal pressure*. Other factors influence this equipment's definition and consequential costs, such as temperature and water depth; however, they were kept constant in this work.

The values adopted for *flowrate* and *dissolution time* were compiled from the already mentioned salt cave studies (Costa et al., 2017, 2019a). The adopted values of flowrate mainly concern the current capacity of injection pumps. The dissolution time to reach the required volume is expected to occur between 2 and 3 years.

Table 2 shows the dependency matrix between the Attributes and the Design Variables adopted for the present evaluation. The superscript number indicates the paragraph description in the following list.

TABLE 2 Design Variables and Attributes dependency.

Attribute	Driller	Nominal Diameter	Nominal Pressure	Dissolution System	Dissolution Flowrate	Dissolution Time
Flowrate capacity		x(1)	x(2)			
Volume capacity					x(3)	x(4)
Environmental Impact				x(5)	x(6)	x(6)
Safety	x(7)		x(8)	x(9)	x(10)	

- **Flow rate capacity**
  (1) According to Bernoulli's principle, the diameter and pressure are related to the flowrate capacity. Using a system with a larger diameter keeps the fluid's velocity smaller for the same flowrate, which is essential to avoid high pressure, vibration, and leakages.
  (2) Systems designed to deal with higher pressures can operate at higher flowrate.
- **Volume capacity**
  (3) Controlling the dissolution time of the cave, an increase in the water injection rate leads to a proportional increase in the quantity of diluted salt and the final volume of the reservoir.
  (4) Prolonged water injection will result in more significant salt dissolution, increasing the cave's dimension.
- **Environmental Impact**
  (5) Assuming that the FPSO is already in operation and its resources will be shared to dissolve the cave, the environmental impact just for dissolving the cave will not be significantly more significant than the existing operation. However, a dedicated unit will consume more fuel, mainly for Dynamic Positioning and operating a submerged pump.
  (6) Considering that a significant parcel of the environmental impact of the salt cave construction is primarily attributed to the substantial amount of brine dispersed onto the seafloor, it is noteworthy to state that the greater the flowrate and duration of the dissolution process, the more prominent will be the environmental footprint.
- **Safety**
  (7) The selection of the driller is determined by its operability, which is directly linked to the vessel's features. For instance, units equipped with Dynamic Position (DP) systems are safer than vessels with conventional anchoring systems.
  (8) It is necessary to consider the nominal pressure of a system when assessing its safety. The higher the nominal pressure, the greater the probability of problems, such as leaks. Therefore, it is crucial to ensure proper measures are taken to maintain the system's safety, especially when dealing with high nominal pressures. By doing so, we can prevent potential hazards and ensure that the system operates smoothly and efficiently.
  (9) The dissolution system also impacts general safety. The FPSO is a floating unit with functions and operations well established, i.e., the crew is very specialized in operating a hazardous system in extreme environmental conditions. New functions can be stressful and put other activities in danger. The crew can focus on a single task if a dedicated unit is chosen so it can improve the system's safety.
  (10) Operating a hydraulic system at a high flowrate can be risky for the integrity of the equipment, potentially leading to a reduced lifespan of connections, piping, and valves.

Safety is the more complex attribute since it depends on the entire system working together. Some additional aspects of the salt cave risk analysis can be found in Pestana et al. (2019) and Pestana et al. (2020).

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

The salt-cave model constants are mainly concerned with factors such as cave and FPSO relative location, depth, and vertical dimension of the salt layer about 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, some classes of operations and equipment are always the same, regardless of the solution. For example, all alternatives must pass the same safety and integrity tests.

3 | SYSTEM EVALUATION AND EPOCH-ERA ANALYSIS

3.1 | Evaluating System Utility

The system can be assessed by defining a single value expressing stakeholder satisfaction. This value is generally defined as the system utility, usually between 0 and 1, where 0 represents a system with minimal acceptable value, and 1 represents a system that delivers the highest possible value.

The utility can be determined by evaluating the system attribute and using Multi-Attribute Utility Theory (MAUT), as presented in Keeney and Raiffa (1993). Each attribute depends on a subset of the Design Variables. For example, evaluating flowrate capacity depends on the nominal diameter and pressure. Then, each attribute value X_k will have an associated single-attribute utility function U_k. The procedure can be summarized as follows:

1. Model a design alternative as a set of design variables. Example : $\{DV_i, DV_{i+1}, ..., DV_n\}$, where n is the number of design variables
2. Evaluate attributes as functions of design variable subsets. Example: $X_k(DV_i, DV_{i+2})$, $X_{k+1}(DV_{i+1}, DV_{i+2})$.
3. Evaluate utilities as functions of attributes: $U_k(X_k)$.

Equation (1) presents the multi-attribute aggregation function used to evaluate the overall utility U.

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

in which N is the number of considered attributes, w_k is the weight of each attribute accordingly to the stakeholder expectation and respecting the Eq. (2).

$$\sum_{k=1}^{N} w_k = 1 \tag{2}$$

In the present work, it was considered that all four attributes have the same weight $w_k = 0.25$. Thus, an example of the utility functions used in the salt cave system is presented in Fig. 6.

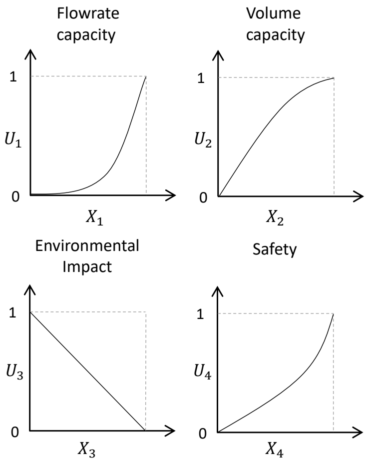


FIGURE 6 Utility functions for each salt cave system attribute.

3.2 | Modeling System Costs

In addition to calculating the utility, estimating the involved costs for each generated solution is necessary. This estimation is initially just for decision-making purposes; precision in the values is not the main objective. Still, future phases can use the collected data to perform a more improved financial feasibility analysis. At this phase, obtaining an order of magnitude for the relative costs of the various concepts is sufficient.

The adopted methodology is presented in Bai and Bai (2018), which consists of obtaining the cost of the standard setup of equipment C_0 and multiplying by cost-driving factors f_i to obtain the total cost (C_{total}) of each equipment. A correction cost C_{corr} can also be applied, as shown in Eq. (3):

$$C_{total} = C_0 \cdot f_1 \cdot f_2 \cdot f_3 \cdot \ldots + C_{corr} \tag{3}$$

Cost-driving factors such as equipment type, pressure, bore size, or any other characteristic that impacts equipment price can be specified. For example, the cost of 7-inch equipment can be 1.2 times that of the standard setup of the same equipment with a 5-inch bore size. These factors are obtained as a function of design variables.

Additional costs, such as Drill Ship, Platform Supply Vessel (PSV), Offshore Supply Vessel (OSV), Pipe Laying Supply Vessel (PLSV) chartering, or consumable utilization, have been considered according to the average market price and the amount of 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. Table 3 presents the dependency between each cost component and the design variables.

TABLE 3 Design Variables and Cost Components dependency.

Cost Component	Driller	Nominal Diameter	Nominal Pressure	Dissolution System	Dissolution Flowrate	Dissolution Time
CAPEX		x	x	x		
OPEX	x	x	x	x	x	x

Due to the information confidentiality, the costs will be presented as non-dimensional values, where 1 represents the solution with the highest cost. The materials and equipment used for the cost estimate are presented in Appendix A. Some items in the list are just used depending on the solution adopted for dissolution (DU or FPSO).

3.3 | Multi-Epoch Analysis

The context of an Epoch is described by the combination of the *Epoch Variables*. For example, a technologically satisfactory system in a given political context may not meet expectations if there is a sudden change in this scenario. Another important aspect is the development of new technologies that make the system lose or gain importance.

At this point, the definition of "value robustness," as detailed in Ross et al. (2008), is necessary to understand the main aspects of the salt cave design. As it is a pioneering, innovative system project with preliminary case studies to understand its strengths and weaknesses, it is necessary to consider the possibility of substantial changes, even in the initial phases. Thus, a feasible solution has value robustness if it continuously delivers value despite the changing context.

Considering the main aspects of the salt cave system design described above, four important epoch variables were considered to describe the context in which the design is inserted. These variables are divided into four areas: environment, market, regulation, and technology. The variables adopted for modeling are presented in detail in Table 4.

TABLE 4 Epoch Variables considered for the salt cave design.

Category	Epoch Variables	Unit	Values
Environment	CO_2 production rate	Level	low (▼) medium (■) high (▲)
Market	CO_2 emission price	U$/t	15; 25; 35
Political / Regulation	CO_2 emission target	volume	decrease (↘) maintain (→) increase (↗)
Technology Development	Reinjection technology	binary	no (✗) - yes (✓)
		Total number of Epochs:	**54**

Gas production rates are expected to fluctuate during the salt cave lifecycle. Thus, in scenarios with high gas production, designs with a high storage capacity and an increased ability to drain that production will be more attractive to stakeholders. These attributes no longer engage in low-production scenarios and are unattractive due to their high cost.

Besides, governments seek to reduce polluting gas emissions and try to do so in various ways. Pricing the CO_2 emissions is an effective way to mitigate air pollution. In this market, CO_2 is a commodity; depending on the price during the lifecycle, the system can deliver more or less utility to the stakeholders. In another way, international agreements set gas emission targets focusing primarily on mitigating global warming. Recent data from World Bank (World Bank, 2021) point out that the price of carbon emissions needs to cost around \$100/t to achieve the goals of the Paris Agreement by 2050. However, the global average is well below that, around \$2 to \$3 per ton (Bhat, 2021).

This work adopted an intermediate and more realistic value (varying from \$15 up to \$35 per ton) since carbon is not yet priced in the Brazilian market and many other important markets. These agreements may change over the years, resulting in different scenarios.

Furthermore, one variable that can change the system's effectiveness is the development of new technology for gas reinjection in production wells. Current technologies often cannot be used as they result in high recycling rates of the injected gas. Still, new technology can significantly reduce the need to store this gas.

In our approach, each Epoch Variable impacts only the customer expectations on the Attributes, which can reflect negative, neutral, or positive outcomes. For example, the CO_2 production rate positively impacts the flowrate capacity, which means that the utility of a system with high flowrate capacity is more significant in a scenario with high CO_2 production. However, the same system could have less utility with new reinjection technology. Considering the salt cave system's epoch variables and attributes, defining an impact matrix as presented in Table 5 is possible.

Each element of the impact matrix M_k^j is, in practice, a multiplier of the utility function U_k at a given epoch j:

$$U_k^j = M_k^j \cdot U_k(X_k) \tag{4}$$

Solutions with high utility for a given attribute will be compensated if that attribute is most relevant at a given epoch and will be penalized otherwise. Depending on the analyzed epoch, the solution can be penalized in one attribute and compensated in another. Thus, the matrix does not impact all alternatives similarly. It will depend on which attribute has greater relevance for that solution.

TABLE 5 Impact Matrix.

	Epoch Variables										
Attribute k	**CO2 Production Rate**			**CO2 Emission Cost**			**CO2 Emission Target**			**Reinjection Technology**	
	▼	■	▲	\$15/t	\$25/t	\$35/t	↘	→	↗	✘	✔
Flowrate capacity	0.70	0.85	1.00	0.90	0.95	1.00	0.80	0.90	1.00	1.00	0.90
Volume capacity	0.90	0.95	1.00	0.90	0.95	1.00	0.70	0.85	1.00	1.00	0.70
Environmental Impact	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.95	1.00	1.00	0.90
Safety	0.90	0.95	1.00	1.00	1.00	1.00	0.90	0.95	1.00	1.00	1.00

By combining the Epoch variables, 54 different epochs were obtained, as shown in Table 12 presented in the Appendix B. The Utility vs. Cost Tradespaces plots for these Epochs are presented in Fig. 7. Each point represents a feasible design within an Epoch, each Epoch set is plotted in a different color, and the blue line represents the Pareto Boundary (or Pareto Set).

Several possible metrics to analyze each solution space obtained for each Epoch. The work of Ross et al. (2009) presents some interesting points described in this section. In an optimization problem with two objective functions, it is possible to group the feasible solutions not dominated by any other in a set called Pareto Boundary.

Smaling (2005) extended this concept, defining the Fuzzy Pareto Frontier evaluation from the "fuzziness factor" (K), which establishes a distance from the non-dominated set based on the data range. In addition to the dominant solutions, the Fuzzy Pareto Set also collects the feasible solutions closer to the Pareto Boundary within the area defined by the K factor.

Smalling also suggests that larger K values should be chosen in the initial design stages, where uncertainties tend to be more significant. Small K values can be taken as the concept matures with more precise and relevant information.

An example of obtaining the Pareto Set is shown in Fig. 7. In this figure, each point is a viable solution belonging to the Tradespace of one of the evaluated epochs. The blue line is the Pareto boundary that contains the dominant solutions.

In the example presented in Fig. 8, it was obtained 486 viable solutions represented by dots. Blue dots represent solutions using a dedicated unit. The red dots represent the solutions using the FPSO resources. The magenta line is the Pareto Boundary. The highlighted numbers are the IDs of the solutions belonging to the Pareto Boundary. The area highlighted in blue represents the Fuzzy Pareto Set considering a 10% fuzziness factor ($K = 10\%$).

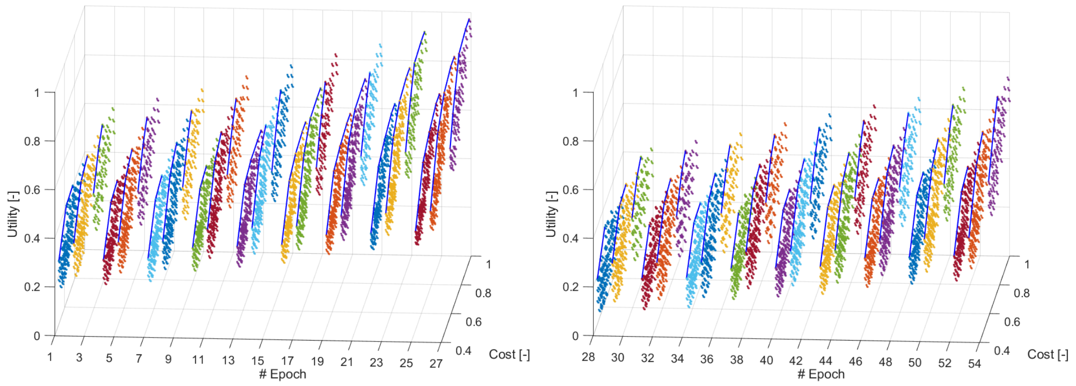


FIGURE 7 Utility vs. Cost Tradespace. Left: Epochs 1 to 27. Right: Epochs 28 to 54.

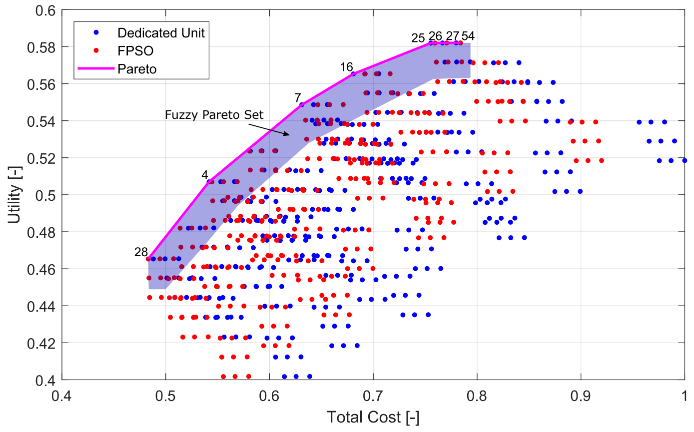


FIGURE 8 Example of Tradespace evaluation showing the Pareto Set and the Fuzzy Pareto Set ($K = 10\%$) for a given “Epoch”.

This above analysis is the so-called Multi-Attribute Tradespace Exploration (MATE) and is carried out for each Epoch. Counting the solutions belonging to the Pareto Set and the Fuzzy Pareto Set, it is possible to evaluate the pa-

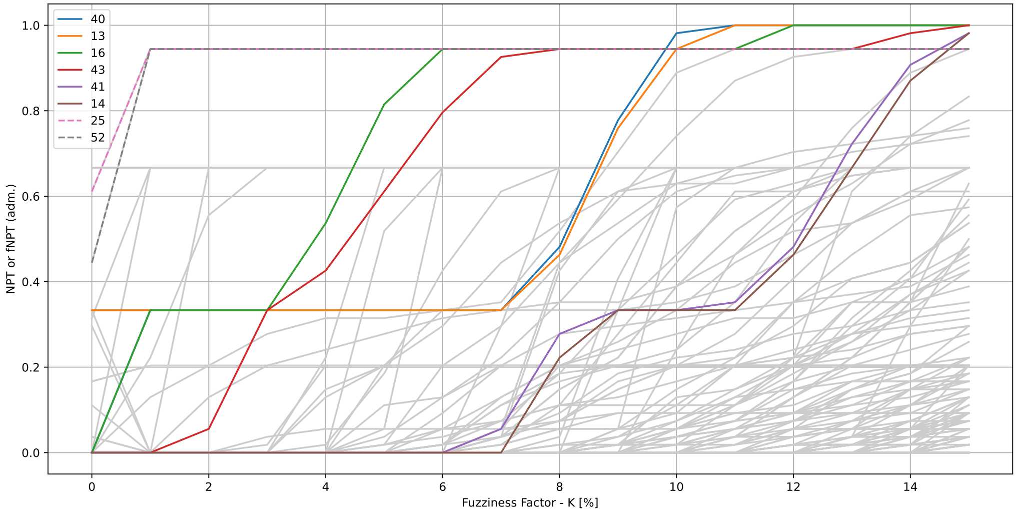


FIGURE 9 Normalized Pareto Trace (NPT) or fuzzy Normalized Pareto Trace (fNPT) for each solution as a function of Fuzziness Factor (K). Highlighted solid curves: Solutions that achieve fNPT > 98%. Highlighted dashed curves: Solutions that achieve a high fNPT for small K.

rameters NPT (Normalized Pareto Trace) and fNPT (fuzzy Normalized Pareto Trace), respectively. The NPT is assessed by performing a count of the number of Epochs in which a given solution appears in the Pareto Boundary ($K = 0$) divided by the total number of Epochs. The fNPT is evaluated similarly but considering the solutions belonging to the Fuzzy Pareto Set ($K > 0$).

A solution with NPT or fNPT equal to zero does not appear in the Pareto set at any of the evaluated epochs. On the other hand, if this value is equal to 1, the solution is contained in the Pareto set for all evaluated epochs. Thus, the higher the NPT/fNPT of a given solution, the greater the value robustness of that design.

Figure 9 shows the NPT/fNPT for each solution as a function of the fuzziness factor (K) varying between 0% and 15%. The highlighted solid curves correspond to the solutions 40, 13, 16, 43, 41, and 14 that achieve fNPT > 98%, i.e., belong to the Fuzzy Pareto Set in at least 55 epochs among the 56 analyzed epochs.

The solutions preference order was obtained according to two criteria. First, it is ordered by the solution that reached fNPT = 1 for the smallest value of K. In the case of a tie, it is ordered by the solution with the largest fNPT in the previous K value.

Furthermore, it is possible to highlight solutions 25 and 52 that present a high fNPT even for a small K. They achieved fNPT > 96% just relaxing the K factor to 1%, i.e., these solutions are at most 1% distant from the Pareto curve in 96% of the analyzed epochs.

Table 6 presents the potential best solutions selected from the above-mentioned ranking. Regarding these solutions, we can mention a clear prevalence of small caves, defined by the minimum values of *Flowrate* and *Dissolution Time* that appear in all solutions in this table.

TABLE 6 Potential best solutions selected from the Multi-Epoch Analysis.

# Design	Driller Operability (%)	Nominal Diameter (in)	Nominal Pressure (ksi)	Dissolution System	Dissolution Flowrate (m^3/h)	Dissolution Time (days)	Normalized Cost (adm.)
40	90%	5	10	FPSO	500	730	0.581
13	90%	5	10	DU	500	730	0.582
16	90%	7	10	DU	500	730	0.681
43	90%	7	10	FPSO	500	730	0.692
41	95%	5	10	FPSO	500	730	0.592
14	95%	5	10	DU	500	730	0.593
25	90%	7	15	DU	500	730	0.755
52	90%	7	15	FPSO	500	730	0.759

Another interesting point is that the model appears somewhat independent of the dissolution system since the chosen solutions appear in pairs. This variable probably has a minor impact on the system cost and utility than the other factors.

Solutions 25 and 52 are similar to solutions 40 and 13 despite the large diameter and higher pressure. These characteristics are necessary to obtain the high fNPT for K = 1% mainly due to the dependency of the attribute *Flowrate capacity*. However, comparing the solutions costs, solutions 25 and 52 are more expensive than the others selected in the above table, showing that the high flowrate capacity has a major impact on the system's costs.

As mentioned, each Epoch comprises exogenous project factors directly impacting its utility and cost. The single epoch evaluation presents the solutions that are good in the short term. However, as presented above, the multi-epoch evaluation presents which solutions are more robust, i.e., they do not change the value perception even in uncertain scenarios with significant context changes.

3.4 | Era Analysis

The Multi-Epoch analysis provided the potential solutions combining all possible generated contexts. However, as pointed out by Schaffner (2014), this analysis does not consider any temporal aspect of the system in its evaluation, nor does it address the transition between different contexts.

To expand the insights the Multi-Epoch Analysis provides, we can perform the so-called "Era Analysis," which is composed of the temporal succession of a defined number of Epochs whose set is called "Era". Within an Epoch, the context is fixed, and between two epochs, the context may or may not vary, resulting in a different assessment of the solution space.

The computation cost of composing and evaluating the entire Eras space by ordering all possible combinations of Epoch variables is excessive and unjustified. Stakeholders with different profiles also will give preference to an analysis in different scenarios according to their expectations. Thus, the Era composition is based on the stakeholder's market prognosis over the system's lifetime.

This way, the Epochs are selected to compose a timeline that describes the evolution of the context variables accordingly to the stakeholders' temporal expectations, such as low risk, high risk, growing market, etc. Therefore, the subset of chosen epochs reflects these expectations into measurable temporal changes.

Thus, the Era Analysis may provide the solutions set with greater value robustness in the long run. In contrast, a Single Epoch evaluation describes the promising solutions in the short term.

To effectively create an Era, a set of transitional rules for combining two consecutive Epochs must be clearly defined. In the present example, two interface rules were adopted to deal with changes in the *CO_2 production rate* and the *Reinjection Technology*:

1. The level of the *CO_2 production rate* can not change abruptly from “low” (▼) to “high” (▲) or vice-versa. In the interface between two Epochs, this level can remain the same or change (grow or decrease) as long as it always passes through an intermediate level.
2. Within an Era, the *Reinjection Technology* cannot change from “yes (✔)” in a previous Epoch to “no” (✘) in the following one. So it can always remain “yes” (✔), always remain “no” (✘), or change from “no” (✘) to “yes” (✔) just once.

The production of CO_2 is an inherent parameter of the oil and gas wells being explored in the locality, and changes in this parameter generally happen slowly. Adopting a rule that the level cannot change abruptly prevents unrealistic scenarios from being explored. The second rule addresses the possible emergence of a new gas reinjection technology in production fields. Once the knowledge is established, it permanently impacts the demand for gas to be stored in the cave as it becomes a competing technology.

The other two epoch variables do not have defined rules because any change is possible and coherent. Since these variables depend on economic and political factors, they can change suddenly, even with abrupt declines or increases.

This work defined an Era as a set with 16 successive Epochs for six months each. In total, there are eight years divided into six months for drilling, two years for dissolution, five years for the operation, and six months for the cave decommissioning. The duration of each Epoch can be dynamically addressed or triggered just when a significant context change occurs. However, keeping this duration constant in a preliminary analysis is reasonable. A semester is judged long enough to capture market trends and evaluate them according to the stakeholders’ expectations. So, two different Eras were composed and assessed based on the following narrative script:

- *Era 1* describes a scenario in which the salt cave stores gas from a well that initially produces a large amount of gas and, after a few years of extraction, this production begins to decline. Emission targets remain average, and there is no significant change in gas reinjection technologies over the system’s lifetime. In parallel, the price of CO2 emissions increases every five or six months. The Era 1 scenario is presented in Table 7.
- *Era 2* describes a scenario of constant CO_2 production since the cave can receive gas from different locations with low demand. The emission price increased in the transition from stage 2 to 3. The emission reduction target has increased in the last three years. Finally, a new gas reinjection technology appeared on the market in the middle of its useful life, four years after the beginning of the construction of the system. The Era 2 scenario is presented in Table 8.

Given that an Era refers to forecasting future scenarios, it is assumed that earlier chosen Epochs are more likely to correctly reflect the context than later ones. This work proposes to address the temporal uncertainty by adopting a linear function that assigns greater weights to early Epochs and smaller weights to late Epochs.

As the “Salt Cave” concept is new, little data is available to accurately estimate a fair weighting to each Epoch in the total Era utility. The model described here supports any probability distribution and does not necessarily reflect an accurate forecast. To illustrate the method, an “educated guess” was taken by assigning a higher weight to the first Epoch and decreasing the weight of subsequent epochs by 2% to account for stakeholders’ uncertainty. It is fairer to

TABLE 7 Era 1 - Temporal evolution description.

Era	8 years															
Epoch Sequence	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Stage	1	2				3										4
Epoch ID #	12	12	12	12	12	12	15	15	14	14	14	17	17	17	17	17
CO_2 production rate	▲	▲	▲	▲	▲	▲	▲	▲	■	■	■	■	■	■	■	■
CO_2 emission cost	15	15	15	15	15	15	25	25	25	25	25	35	35	35	35	35
CO_2 emission target	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Reinjection Technology	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
Weight	100%	98%	96%	94%	92%	90%	88%	86%	84%	82%	80%	78%	76%	74%	72%	70%

Stages: 1 - Drilling, 2 - Dissolution, 3 - Operation, 4 - Abandonment.

TABLE 8 Era 2 - Temporal evolution description.

Era	8 years															
Epoch Sequence	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Stage	1	2				3										4
Epoch ID #	10	10	10	10	10	10	13	13	40	40	49	49	49	49	49	49
CO_2 production rate	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
CO_2 emission cost	15	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
CO_2 emission target	→	→	→	→	→	→	→	→	→	→	↗	↗	↗	↗	↗	↗
Reinjection Technology	✘	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔	✔	✔	✔	✔	✔
Weight	100%	98%	96%	94%	92%	90%	88%	86%	84%	82%	80%	78%	76%	74%	72%	70%

Stages: 1 - Drilling, 2 - Dissolution, 3 - Operation, 4 - Abandonment.

present a model that can account for weight decrease due to uncertainty rather than linearizing all the Epochs.

The designs that performed better in the last Epochs are penalized compared to the good ones from earlier Epochs. Another aspect is that within an Era, some Epochs are repeated once there are no changes in the external context between two consecutive epochs. If a defined Epoch appears several times, the designs that perform well in this Epoch have more chances of having great value to the stakeholders in the long run.

Again, when searching for "value robustness" across the Eras, obtaining the designs with the greater NPT/fNPT for a minimum K value is crucial. From the scenarios defined in Table 7 and Table 8, it is possible to assess the NPT/fNPT for each Era. However, unlike Multi-Epoch Analysis, we have to deal with the defined weight for each Epoch.

As explained in Fitzgerald and Ross (2012), the NPT/fNPT can be quickly evaluated from the "Fuzzy Pareto Number" (FPN). The FPN is the smallest K value for which a design (d) belongs to the fuzzy Pareto set (P_K) of an Epoch (e):

$$FPN(d,e) = min\left\{K | d \subset P_K(e)\right\} \tag{5}$$

Thus, the NPT/fNPT considering the proposed weighted scheme (wNPT/wfNPT) along the Era can be evaluated as:

$$wfNPT(d) = \left[\sum_{e=1}^{N_E} (w_e \cdot f_e(d,K)) \right] \div \sum_{e=1}^{N_E} (w_e) \tag{6}$$

Where w_e is the weight for each Epoch as defined in Tables 7 and 8, N_E is the number of Epochs considered along the Era and $f_e(d,K)$ is a function such that:

$$f_e(d,K) = \begin{cases} 1 & \text{if} \quad FPN(d) \le K \\ 0 & \text{if} \quad FPN(d) > K \end{cases} \tag{7}$$

When performing the mentioned analysis, we can rank the potential reasonable solutions for each Era according to the wNPT/wfNPT. Adopting the same ranking rules as explained in Section 3.3, the designs $S_1 = \{25, 52, 4, 31, 26, 16, 53, 43, 17, 40\}$ perform better for Era 1 and $S_2 = \{7, 25, 28, 52, 1, 4, 31, 34, 8, 29\}$ perform better for Era 2.

As noted, designs 25 and 52 appear in the top 10 solutions in both sets. This result is somewhat expected due to the performance of these two solutions in the Multi-Epoch analysis.

The other solutions that deserve attention are design number 4 (90%, 5 in, 5 ksi, D.U., 500 m^2/h, 730 days, 0.542) and its counterpart solution number 31 (90%, 5 in, 5 ksi, FPSO, 500 m^2/h, 730 days, 0.544). These are the smallest possible configurations once it is composed of the minimum values adopted in the Design variable range, except by the value of nominal diameter (minimum nominal diameter is 3 inches).

Again, these solutions show that taking the Nominal Diameter or the Nominal Pressure greater than the minimum value is a good choice. Although this may result in a more expensive layout, the system's utility is rewarded, resulting in more value-robust designs.

Given the results obtained in the Multi-epoch and Era analyses, observing the terms presented in this work, solution 25 or solution 52 would be chosen as the initial configuration to develop the cave project if it weren't for the high cost compared to other solutions with value robustness.

A point that deserves consideration when choosing one of the highlighted solutions is that no offshore salt caves are built or in operation. Naturally, stakeholders will initially choose alternatives requiring less investment, first to validate the concept and acquire the confidence to develop other caves. In this way, probably chosen solution 4 or 31 is more interesting.

4 | DIGITAL TWIN SALT CAVE CONCEPT

4.1 | Rationales for Digital Twin Concept and Development

The concept studies developed for the CCS system as a motivation to explore the potential of digital twins supporting the salt cave project and operation. Rebentisch et al. (2021) proposed applying a Concept of Operations (CONOP) analysis to translate high-level digital twin objectives into an actionable system concept. The work presents a typical CONOP analysis composed of seven stages. The research includes an introductory overview of the envisioned system; a list of goals, objectives, and rationale for the system linked to the overall strategy; a system concept describing the envisioned system with its elements and relations in both technical and social domains; major work processes to be automated or supported by the system; functional and non-functional requirements at system-level including operating environment concerns; users, use cases, and their relationship to system capabilities; and finally considerations on potential risks, issues, and organizational impacts.

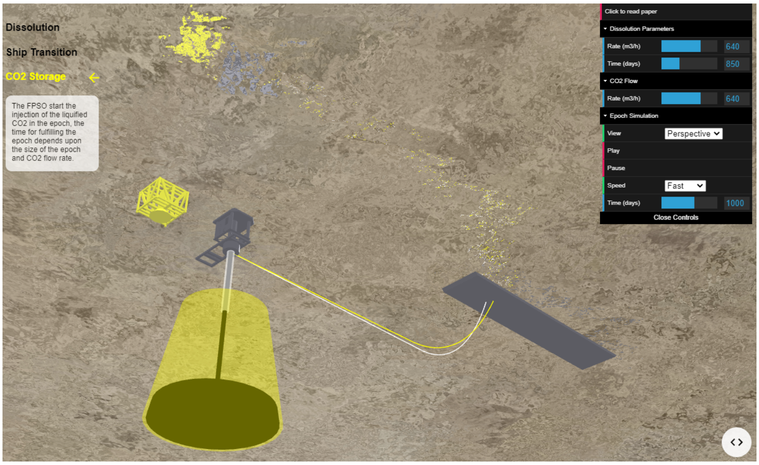
This section uses the mission statement and system model presented in Section 2 as input to a preliminary CONOP analysis of a digital twin CCS salt cave. Two rationales for digital twin development are investigated, one primary and one secondary, to identify its potential benefits. The primary digital twin rationale is to support effective salt cave design and execution, including monitoring and controlling dissolution and operation from a central hub. As Section 2.1 briefly explained, the study started modeling the CCS salt cave as a system, including formulation of the mission concept, identification of attributes, mapping of design variables, and consolidation of the gathered information into a system model. Sections 4.2 and 4.3 take the system model developed in Section 2.1 as an input to elucidate the requirements expected from a successful digital twin as support to salt cave design, dissolution, and operation of CCS salt cave. More specifically, Section 4.2 presents initial work on salt cave visualization and simulation as a starting point for future digital twin development.

With the CCS system model already formulated, Section 3.1 took it as a starting point to evaluate system performance and utility subject to various conditions. This was done through a Multi-Epoch analysis for assessing system utility in different scenarios and then with an Era analysis for concatenating the assessed utilities on alternative lifecycle realizations. As the salt cave is an innovative system, the digital twin should also be used as an opportunity for stakeholders to better understand system performance in different contexts throughout the lifecycle and consolidated by empirically measured behavior. Thus, the secondary digital twin rationale is to provide a structured feedback loop between the analyses modeled so far and the observed system behavior during operations, to improve the design of similar systems. This rationale is outlined in Section 4.4. Finally, Section 4.5 comments on continued digital twin development and eventual deployment.

4.2 | Virtual Prototyping During Design Stage

During early stage design, it is possible to make virtual prototypes of different salt cave alternatives to evaluate their performances concerning economic feasibility or high-level behaviors and then convey the results of such analyses to stakeholders. A web-based simulation and visualization of the salt cave concept were developed as a starting point toward these objectives (Vieira et al., 2020). Existing web-based technologies already provide rich resources for creating user interfaces, from conventional graphical user interfaces to realistic 3D scenes linked to virtual reality applications. In developing innovative projects, such visualization tools can clearly and objectively communicate design concepts and operational states to stakeholders, elucidating their questions.

The arrangement of the well pipes and the dissolution process generating the cave shape was modeled as predicted by Costa et al. (2019a). The application considers an epoch where a dedicated vessel carries out dissolution for a given number of days and with a specified dissolution rate. In the transition phase, the vessel is replaced by an FPSO unit, which connects to the umbilical and injection riser to start operation, meaning CO_2 storage at a given flow rate. The simulation continues until the salt cave is filled to its maximum capacity. Fig. 10 presents a screenshot of the model, in which it is possible to observe the floating units, the umbilical cables, and the catenary risers. The app also shows the equipment involved in the operation, such as submerged pumps, wellhead, and Christmas tree. While the physical components displayed in the visualization are fixed, the user can configure some design variables and observe their effect on the simulated epochs. The graphical user interface provides controllers to set the cave dissolution rate and time parameters as shown in Table 1, the rate of CO_2 flow injection into the cave, buttons to start, pause, or restart the simulation, and an indicator showing the elapsed time.



The FPSO start the injection of the liquified CO2 in the epoch, the time for fulfilling the epoch depends upon the size of the epoch and CO2 flow rate.

Dissolution Parameters
Rate (m3/h) 640
Time (days) 850

CO2 Flow
Rate (m3/h) 640

Epoch Simulation
View Perspective
Speed Fast
Time (days) 1000

FIGURE 10 Screenshot of the Salt Cave Visualization Module Implemented in the Vessel.js Platform. Available at https://vesseljs.org/.

The three-dimensional salt cave model was implemented with the Vessel.js library (Gaspar, 2018), an open-source JavaScript library to visualize and simulate marine engineering systems and operations. Fonseca and Gaspar (2019) discusses the advantages of a web-based approach to developing collaborative simulations, exemplifying functionalities implemented in Vessel.js. Among the benefits of web-based solutions is the compatibility with standard web browsers, making further software installation unnecessary and thus increasing the potential for scalability.

A handful of new features were implemented to model the salt cave system environment with the library. 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 initial implementation, the model has the sole purpose of visualizing the solutions developed by the systems engineering model.

Future work should link this visualization to the modeling parameters considered in the Epoch-Era Analysis to enhance the virtual prototype's capabilities. The tool would be expanded with a catalog of subsystems documented with their design variables and the corresponding cost. It would allow the quick generation of alternative system concepts, such as those shortlisted in Table 6. Once a system concept is selected, its corresponding virtual prototype can be detailed during subsequent design stages and then developed into a digital twin to support cave dissolution and operation. For instance, the process of cave dissolution might take years to complete, opening the margin for changes in the operational context, which are reflected in the current epoch variables and the stakeholder's expectations for the ongoing era. If this leads to reevaluating the desired cave capacity, the digital twin might be used to simulate the remaining dissolution time accordingly.

4.3 | Digital Twin as Support to Dissolution and Operation

The digital twin applications can be extended beyond simulation and visualization for design. During the stages of dissolution and operation, the longest ones in the cave's lifecycle, it might be used to integrate the relevant models for involved disciplines. The simulation models can be informed by the current salt cave's functional state by linking to measurements in real-time, allowing stakeholders to monitor its operation and plan for appropriate intervention measures when needed.

The mission description (Section 2.2) and the four system attributes, as explained by Section 2.3 presents), might guide purposeful planning of the use cases, simulation, and data acquisition pipelines from salt cave attributes to simulation modules for the first digital twin rationale. At a high level, different system attributes might be linked to a simulation module, as follows:

- Flowrate Capacity: Flow Assurance
- Volume Capacity: Storage Utilization
- Environmental Impact: Flow Assurance
- Safety: Structural Health

During dissolution, it is necessary to verify that the brine is dissolved safely until the cave has reached the desired capacity. At the same time, the cave should always have enough pressurized liquid to maintain its structural integrity and avoid implosion. The instrumentation setup should measure the disposal flow in the brine suction pump, and the digital twin would simulate the salt cave volume until the desired capacity is reached. The pressure gauges on the injection and return pipes would indicate whether the working pressure in the dissolution system and the internal pressure of the salt cave are maintained at the desired level. Additional instrumentation setups in the dissolution system and possibly seabed could simulate and evaluate the structural integrity of the cave, wellhead, and XT.

After the cave has been built, the digital twin might be used to monitor and possibly automate safe and effective operations. During operation, some of the construction concerns remain; ensuring an environmentally friendly brine disposal rate and a sound cave structure is necessary. In addition, the operation needs to reconcile these factors with the injection of CO_2 into the cave. The digital twin should then assess the gas production rate from the FPSO and control the transmission flow rate from FPSO toward the cave. As the gas enters the storage, the digital twin should sense the salt cave's outlet pressure, and when that pressure reaches a certain threshold, it should dispose of the excess brine at a safe flow rate for the environment and the cave's structure. Table 9 summarizes these use cases.

While the individual use cases listed in Table 9 do not differ much from standard electro-mechanical control systems, the digital twin combines them in a single 3D interface which allows the user to monitor and control various system aspects. This enables the integration of separate control modules into a central hub for interaction with the salt cave, similar to the case study presented by Fonseca et al. (2022).

4.4 | Potential of Using Digital Twin as Tool for EEA Tuning and Validation

As Section 1.2 briefly commented, EEA modeling accounts for five aspects of system complexity, namely, structural, behavioral, contextual, temporal, and perceptual. Structural aspects relate to the system's form and components, and behavioral to performance, operations, and stimuli reactions. These two aspects correspond roughly to traditional systems engineering approaches focused on ensuring a system exists and behaves as specified by stakeholders. The three remaining aspects extend EEA beyond evaluating system form and function toward strategies for value robustness considering long-term uncertainty (Rhodes and Ross, 2010). Contextual relates to system performance under different circumstances. Temporal relates to the interplay between system aspects over time. Finally, perceptual refers to stakeholders' views and preferences.

The secondary digital twin rationale is to evaluate and adjust the Epoch-Era Analysis based on data gathered during the salt cave's lifecycle. To organize the rationale, the analyses carried in Section 3 can be mapped to the specific aspects they address:

TABLE 9 Digital twin use cases during cave dissolution and operation stages.

Simulation Module	Stage	Use Case	Data Acquisition
Flow Assurance	Both	• Monitor brine disposal rate. • Pause activities and/or emit CO_2 through secondary sink if amount of brine to be disposed of is bigger than allowed by environmental rules.	• Brine draining flow at wellhead.
Flow Assurance	Operation	• Monitor CO_2 injection rate. • Predict and control amount of brine disposed of in order to admit CO_2.	• CO_2 injection flow at wellhead. • Rate of CO_2 being produced.
Storage Utilization	Dissolution	• Stop dissolution when salt cave reaches specified capacity.	• Total amount of drained brine.
Storage Utilization	Operation	• Phase out admission as cave reaches maximum capacity.	• Total amount of injected CO_2.
Structural Health	Both	• Pause dissolution if generated brine causes excessive pressure. • Pause operation and/or emit gas through secondary sink if CO_2 causes excessive pressure. • Monitor structural stresses imposed to risers.	• Pressures on admission and return pipelines and wellheads. • Wave condition. • Floating structures' motion responses.

- Structural: design variables (Table 1), system costs (Eq. (3) and Table 3). The system structure is defined by its design, which automatically defines its capital costs.
- Behavioral: system attributes (Table 2). The system attributes model its behavior from a purely functional perspective.
- Contextual: Epoch variables (Table 4), multi-Epoch analysis (Fig. 7). The Epoch variables model different circumstances the system may face during its lifecycle, while the multi-Epoch analysis evaluates system value under these circumstances.
- Temporal: Era analysis (Tables 7 and 8). The Era analysis concatenates the Epochs in feasible system lifecycle timelines.
- Perceptual: attribute's utilities (Fig. 6), attribute's weights (Eq. (2)), impact matrix (Table 5). These metrics allow stakeholders to weigh their priorities and preferences in system evaluation.

The list synthesizes the central aspect corresponding to each model or metric used; however, there is an occasional overlap between different aspects. For instance, system attributes, which constitute behavioral metrics, are modeled in Table 2 concerning design variables, which are structural characteristics of the system. Similarly, system costs are mainly a structural characteristic calculated as a function of design variables. Still, they serve as an evaluation metric shaping stakeholders' perceptions about the feasibility of different design alternatives.

This characterization helps identify which factors can benefit from more accurate simulation models or are amenable to validation during system operation. For instance, perceptual aspects such as the choice of utilities, weights, and epoch parameters depend on different stakeholders' value systems and are, to some extent, subjective. Due to its innovative characteristic, another complicating issue is the absence of data from similar systems. The system definition has not yet been settled during the early design stage. If stakeholders want to perform detailed comparisons among design alternatives, they must use pure virtual prototyping techniques as discussed in Section 4.2. This makes it possible to gather insight into the design's functioning or the utilities attained for a combination of design variables.

Once stakeholders commit to a design, they will conduct further analyses, construction, and operation only for the chosen alternative. This lack of data limits the opportunity to compare systems and predict behavior based on operational data in uncertain contexts. It complicates related techniques, such as machine learning, because these methods acquire their accuracy based on training and testing on an underlying statistical distribution realized in a given data set. Thus, the risk of deviation increases when these models are used to predict outcomes in different distributions associated with alternative designs or novel contexts.

Based on that, the digital twin potential to corroborate Epoch-Era analysis relies mainly on the classic model validation sense of ensuring that the attributes predicted based on design variables align with observed system behavior. To achieve this, it is necessary to translate the four general system attributes to more granular metrics suitable for data-based measurement and statistical treatment. Table 10 presents an example of attribute breakdown into metrics stakeholders can use to calculate and predict performance from an operational perspective.

The gathered data allows stakeholders to reconsider whether the early models were adequate and, if not, to re-calibrate the simulation of system attributes concerning design variables and adjust the feasibility range of such variables for future designs based on the findings.

The updated system models might also be used to re-calibrate simulations of different epochs in the Multi-Epoch analysis. As the salt cave is operated on other profiles and the corresponding data is accumulated over time, stakeholders might use it to evaluate the suitability of epoch variables in modeling expected contexts during the cave's operation stage. This includes an improved quantitative treatment of the ranges adopted in Table 4.

As the operation stage progresses, the system faces new contexts characterized by different epoch variables. The digital twin data allows stakeholders to measure system utilization in distinct contexts, obtaining a mapping with correlations between epoch variables and usage of system attributes.

Such mapping can be used to tune or detail the EEA in two main ways, as Fig. 11 illustrates. The first is by re-calibrating expected operation indicators and the remaining life span for a system that has already been built by including more accurate forecasts of subsequent epochs. The second one is by informing concept analyses for similar designs. In case the digital twin data reviews some system attribute, say flowrate capacity, is sub-utilized in a context of high CO_2 production, stakeholders might consider reducing the corresponding impact matrix factors in Table 5 to reflect the relaxed demands placed upon the system in those conditions, and conversely for over-utilized attributes.

TABLE 10 Data gathering plan for measurement of system attributes.

System Attributes	Data Acquisition	Performance Evaluation and Prediction
Flowrate Capacity	• Overloads due to the system being incapable of injecting CO_2 or draining brine at necessary flowrate. • Flowrate capacity utilization over time for injection and return pipelines.	• Calculate downtime and loss of operational effectivity. • Estimate future system overloads.
Volume Capacity	• Cave's volumetric utilization over time.	• Calculate remaining volumetric capacity. • Estimate remaining usable life span.
Environmental Impact	• Brine disposal rate as fraction of maximum allowed quantity over time.	• Calculate amount of disposed brine. • Estimate total amount of brine disposal as of abandonment.
Safety	• Overloads due to the system being incapable of injecting CO_2 or draining brine at the necessary pressure. • Pressure capacity utilization over time for injection and return pipelines. • Motion-induced structural stresses the riser subsystem experienced.	• Calculate downtime and loss of operational effectiveness. • Estimate expected future system overloads. • Calculate riser's fatigue accumulation. • Estimate riser's remaining structural life span.

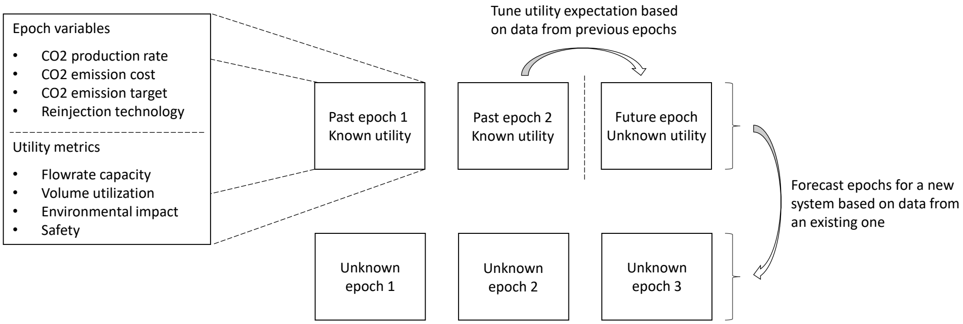


FIGURE 11 EEA tuning and calibration based on digital twin data.

In summary, while there is potential for feedback loops between the salt cave's Epoch-Era analysis and the operational data collected by the digital twin, its realization requires planning and evaluation over a more extended period than the primary rationale. This is because while the analyses focus on relatively long periods, with epochs characterized by changes that evolve over the years, the digital twin collects data on an immediate and ongoing basis, making it necessary to bridge both time horizons. Furthermore, suppose eventual EEA improvements will extend beyond support to the salt cave after it has been built and toward the design of future CCS systems. In that case, it will be necessary to have data governance and sharing guidelines spanning different projects.

4.5 | Toward Digital Twin Development and Deployment

Depending on the state of practice of a given engineering discipline concerning network connectivity and the usage of simulations to aid operational decisions, the threshold for the characterization of a digital twin might become more or less restrictive. For instance, in ship operations, establishing reliable connectivity between ship and shore is often challenging, data management has traditionally been fragmented, and digital tools lack interoperability. Based on that, Agis et al. (2022) argues for a more restrained approach in that field, aiming to synthesize major system concerns into smaller functionalities to increase the feasibility of implementing the digital twin.

On the other hand, the oil and gas sector enjoys more reliable connectivity between the system and shore and better-established data management practices than the ship industry. In that context, Feder (2021) proposes the development of holistic digital twins to integrate all relevant aspects of the drilling value chain. This work follows the former approach by focusing on core digital twin functionalities. Since the salt cave is an innovative system, defining its central capabilities at this stage is more critical. Further work should evaluate the adequacy of broadening the digital twin scope with additional functionalities and eventually refine the proposed concept toward a detailed specification for development and implementation.

Earlier work by the authors grouped the digital twin content into three major groups: a model of the asset and simulation models of its behaviors. It updated measurements from the system and its context (Fonseca et al., 2022). Fig. 12 illustrates these content groups applied to the salt cave case. The salt cave model includes the data necessary to represent relevant aspects of the salt cave's physical constitution, which can roughly be organized into two groups. The first is the site model with topology, geotechnical characteristics, etc. The second is the engineering systems and components installed onto the cave, as modeled in Sections 2.1 and 2.4. Digital components include 3D visualization files and descriptive metadata with identification, functional parameters, costs, etc. These characteristics can be partially modeled during early design and virtual prototyping; others must be gradually detailed as cave design and operation evolve.

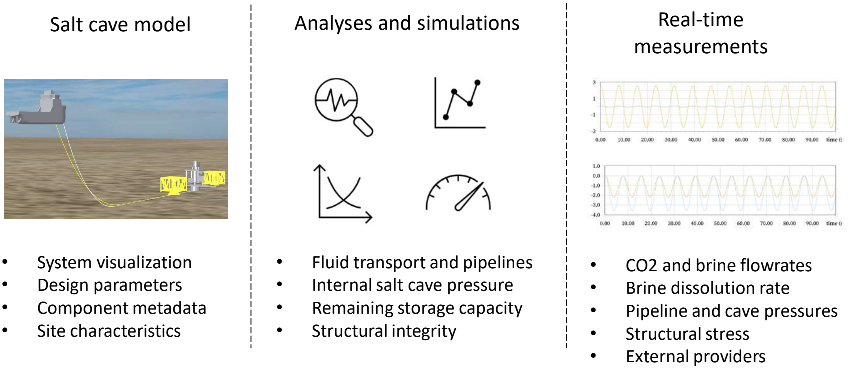


FIGURE 12 Types of content in a digital twin salt cave.

Enabling the simulation and data acquisition plans described earlier requires collecting data from the salt cave through sensors and instrumentation and its surrounding contexts, such as external metocean services measuring wind and hydrodynamic loads. This includes concomitant aspects such as floating response, geomechanics, well engineering, and subsea. With the importance of data in these setups, data quality becomes essential to ensure the digital twin provides adequate decision support.

With the increasing trend toward digitalization, relevant documents are already covering this issue from different angles. For instance, the ISO 8000 standard establishes principles and pathways to data quality from the point of view of governance and business usage (ISO, 2022). The DNV-RP-A204 rule deals with the qualification and assurance of digital twins, accounting for levels of criticality, involved risks, and requirements for verification and validation (DNV-GL, 2020).

Finally, as the system is set to aggregate various data streams and simulations, it is necessary to balance different resources when conveying information to users to avoid overwhelming them with information. The web-based interface provides a basis for developing a digital twin front end. As new simulations are included in the digital twin, they can be linked to specific dashboards displaying interfaces with specialized visualization, data streams, monitoring status, etc. The web-based approach provides tools to communicate these elements clearly and to give users a sense of immediacy when operating assets remotely.

5 | CONCLUSION

This paper illustrates how complementary methods can be combined to tackle different concerns during the lifecycle of complex and innovative systems, specifically a salt cave. During system conception and design, some of the Multi-Epoch and Epoch-Era analyses' strengths are systematically articulating and evaluating diffuse stakeholder concerns.

The Multi-Epoch analysis supports the communication of perceived utilities among stakeholders and mapping such utilities to specific design alternatives through the corresponding design variables. The Epoch-Era analysis provides a tool to assemble hypothetical scenarios and assess the system's value robustness through them. The digital twin is proposed as a tool to support design and operation, and validate some of the developed models based on data collected from the physical system.

The development of the salt caves project for CO_2 storage is strategic for the oil and gas production chain. In addition, reducing greenhouse gas emissions, like carbon dioxide, is the main goal in almost all international environmental agreements. In this context, a system engineering model was employed to provide insights into decision-making in the early stages of the conceptual design of an offshore salt cave system for CO_2 storage.

Given the complexity of carrying out the necessary steps for the implementation of the salt cave project, and given the diversity of the range of correlated areas, added to the fact that the proposed system is endowed with a high degree of technological innovation, the usual design methods can not be the best alternative. The study and application of rational decision-making methodologies considering the different phases, systems, teams, and operation chains increase the project's chances of success.

The Multi-Attribute Tradespace Exploration (MATE) method was used to obtain utility and cost estimates for a set of feasible solutions. From that point on, the system's lifecycle was analyzed using Epochs and Eras that comprise the short and long-term analyses, respectively. For each solution space, evaluation metrics were used to determine the probabilities of the solutions being contained in the Pareto Frontier and the Fuzzy Pareto Set. The greater this probability, the greater the value robustness of delivering the system's value.

In the presented evaluation example, both Multi-Epoch and Era analyses indicated two complementary potential good solutions: Designs 25 and 52. These solutions proved to have greater passive value robustness since they can remain in the set of the best solutions regardless of changes in the scenario due to exogenous factors.

The paper showed how the models produced for the previous analyses can be used to guide scoping of a digital twin to successfully support salt cave design, dissolution, and operation. Both approaches, however, need to be taken as complementary to each other, as a purely data-based approach is not able to fully grasp the considerations required for the design and execution of complex innovative systems.

For instance, outlining a digital twin to support dissolution and operation based on functional needs is relatively straightforward. On the other hand, modeling system performance from a strategic perspective imposes several challenges to a data-based approach.

They include the absence of data about an innovative system during early stage design, the account of (somewhat subjective) criteria stakeholders adopt to evaluate the system, and the contextual uncertainty brought by long operation time spans. For these reasons, the concerted effort of stakeholders toward modeling and evaluating future scenarios through methods such as the Epoch-Era analysis remains essential.

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A | MATERIAL AND EQUIPMENT CONSIDERED FOR COST ESTIMATION

Table 11 presents the list of materials and equipment taken into account in the system engineering model to estimate the associated costs.

TABLE 11 List of material and equipment.

Drilling Phase	Dissolution Phase
• **Casing and Tubing**	• **Lines**
– External Casing	– Umbilical
– Intermediary Casing	– Riser
– Internal Casing	– Flowline
– Brine return tubing	– Contingency Riser
– Sea water 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

B | DEFINITION OF CONSIDERED EPOCHS

Table 12 presents the set of the Epoch Variable values associated with each of the 54 Epochs considered in the present work.

TABLE 12 Description of evaluated Epochs

	Epoch Variable					Epoch Variable					Epoch Variable			
Epoch ID #	**A**	**B**	**C**	**D**	**Epoch ID #**	**A**	**B**	**C**	**D**	**Epoch ID #**	**A**	**B**	**C**	**D**
1	▼	15	↘	✘	**19**	▼	15	↗	✘	**37**	▼	15	⇢	✔
2	■	15	↘	✘	**20**	■	15	↗	✘	**38**	■	15	⇢	✔
3	▲	15	↘	✘	**21**	▲	15	↗	✘	**39**	▲	15	⇢	✔
4	▼	25	↘	✘	**22**	▼	25	↗	✘	**40**	▼	25	⇢	✔
5	■	25	↘	✘	**23**	■	25	↗	✘	**41**	■	25	⇢	✔
6	▲	25	↘	✘	**24**	▲	25	↗	✘	**42**	▲	25	⇢	✔
7	▼	35	↘	✘	**25**	▼	35	↗	✘	**43**	▼	35	⇢	✔
8	■	35	↘	✘	**26**	■	35	↗	✘	**44**	■	35	⇢	✔
9	▲	35	↘	✘	**27**	▲	35	↗	✘	**45**	▲	35	⇢	✔
10	▼	15	⇢	✘	**28**	▼	15	↘	✔	**46**	▼	15	↗	✔
11	■	15	⇢	✘	**29**	■	15	↘	✔	**47**	■	15	↗	✔
12	▲	15	⇢	✘	**35**	▲	15	↘	✔	**48**	▲	15	↗	✔
13	▼	25	⇢	✘	**31**	▼	25	↘	✔	**49**	▼	25	↗	✔
14	■	25	⇢	✘	**32**	■	25	↘	✔	**50**	■	25	↗	✔
15	▲	25	⇢	✘	**33**	▲	25	↘	✔	**51**	▲	25	↗	✔
16	▼	35	⇢	✘	**34**	▼	35	↘	✔	**52**	▼	35	↗	✔
17	■	35	⇢	✘	**35**	■	35	↘	✔	**53**	■	35	↗	✔
18	▲	35	⇢	✘	**36**	▲	35	↘	✔	**54**	▲	35	↗	✔

Legend: A-CO_2 Production Rate; B-CO_2 Emission Cost; C-CO_2 Emission Target; D-Reinjection Technology