Universidade do Estado do Rio de Janeiro
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Development of a Framework for Life Extension Process Management in Offshore Oil and Gas Facilities

Rio de Janeiro
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Tese apresenta, como requisito parcial para a obtenção do grau de Doutor, ao Programa de Pós-Graduação em Engenharia Química, da Universidade do Estado do Rio de Janeiro. Área de concentração: Processos Químicos, Petróleo e Meio Ambiente.

Orientador: Prof. Dr. Marco Antonio Gaya de Figueiredo (UERJ)
Prof. Dr. Marcelo Ramos Martins (USP)
Prof.ª Dra. Rebecca Dziedzic (Concordia University)

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DEDICATÓRIA

Dedico este trabalho a todos que me acompanharam nessa jornada, que é bastante individual e solitária, mas, ao mesmo tempo, é um trabalho de equipe da família, dos amigos, das empresas que abrem seus dados à pesquisa acadêmica, dos orientadores e colaboradores e do empregador que resolve investir em você.

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Para tudo há uma ocasião certa: há um tempo certo para cada propósito debaixo do céu. Tempo de nascer e tempo de morrer, tempo de plantar e tempo de arrancar o que se plantou...

Eclesiastes – Capítulo 3

RESUMO

FERREIRA, N. N. *Desenvolvimento de uma metodologia para gerenciamento de processos de extensão de vida útil em instalações offshore de petróleo e gás.*. 2024. 264 f. Tese (Doutorado em Engenharia Química) - Instituto de Química, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2024.

A extensão da vida útil das instalações *offshore* de petróleo e gás tem se tornado cada vez mais importante devido aos seus potenciais benefícios econômicos e operacionais. No entanto, o processo de extensão da vida útil desses ativos envelhecidos apresenta diversos desafios que devem ser gerenciados para garantir a segurança, a eficiência e a redução da pegada de carbono. Esta tese apresenta um *framework* abrangente para gerenciar o processo de extensão da vida útil, integrando as perspectivas de degradação de materiais, obsolescência, questões organizacionais e considerações ambientais no processo de tomada de decisão, assegurando que as estratégias de extensão da vida útil sejam não apenas econômica e operacionalmente viáveis, mas também ambientalmente conscientes. Um guia estruturado é proposto para avaliar sistematicamente a viabilidade da extensão da vida útil, e etapas são definidas para avaliar os tópicos mencionados acima com intuito de preencher lacunas existentes na literatura e nas abordagens regulatórias, gerar maior respaldo na tomada de decisão e garantir a adoção de estratégias que assegurem a operação segura do ativo e reduzam o impacto ambiental das operações estendidas. Por sua vez, as questões organizacionais, inerentes ao processo de extensão da vida útil, são exploradas através da lente da transferência de conhecimento interorganizacional. Assim, são identificados os elementos-chave e desafios que influenciam o sucesso desse processo e é investigado o impacto de uma transferência mal-sucedida em segurança do processo, particularmente quando o pessoal não é transferido junto com o ativo. A pesquisa fornece ideias para o desenvolvimento de futuras metodologias estruturadas e soluções gerenciais para facilitar a transferência de conhecimento eficaz. Finalmente, esta tese apresenta uma abordagem estruturada para gerenciar a extensão da vida útil das instalações de petróleo e gás, oferecendo frameworks práticos que aprimoram a tomada de decisão nos domínios técnico, organizacional e ambiental, e destaca a necessidade de diretrizes regulatórias aprimoradas.

Palavras-chave: extensão da vida; instalações de petróleo e gás; gestão do envelhecimento; emissão de carbono; ferramenta de tomada de decisão

ABSTRACT

FERREIRA, N. N. *Development of a Framework for Life Extension Process Management in Offshore Oil and Gas Facilities*. 2024. 264 f. Tese (Doutorado em Engenharia Química) - Instituto de Química, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2024.

The life extension of offshore oil and gas facilities has become increasingly important due to its potential economic and operational benefits. However, the process of extending the service life of these ageing assets poses several challenges that must be carefully managed to ensure safety, efficiency, and reduced carbon footprint. This thesis presents a comprehensive framework for managing the life extension process, integrating the perspectives of material degradation, obsolescence, organizational issues, and environmental considerations into the decision-making process, ensuring that life extension strategies are not only economically and operationally viable but also environmentally aware. A structured guideline is proposed to systematically assess the feasibility of life extension, and stages are defined to evaluate the first three topics mentioned above, filling existing gaps in literature and regulatory approaches and supporting more informed decision-making, that guarantee the adoption of strategies that ensure the safe operation of the asset and reduce the environmental impact of extended operations. In turn, the organizational issues inherent in the life extension process are explored through the lens of inter-organizational knowledge transfer (IKT), identifying key elements and challenges that influence the success of this process and investigating the impact of unsuccessful IKT on process safety, particularly when personnel are not transferred along with the asset. The research provides insights for developing future frameworks and managerial solutions to facilitate effective knowledge transfer. Finally, this thesis presents a structured approach to managing the life extension of oil and gas facilities, offering practical frameworks that enhance decision-making across technical, organizational, and environmental domains and highlights the need for improved regulatory guidelines.

Keywords: life extension; oil and gas facilities; ageing management; carbon footprint; decision-making tool

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LIST OF ACRONYMS

AFMEA – Advanced Failure Mode and Effects Analysis

ALARP – As Low As Reasonably Practicable

ANP – Brazilian National Agency of Petroleum, Natural Gas and Biofuels

BCR – Benefit-Cost-Ratio

BSW – Basic Sediments and Water

CCA – Cause-Consequence Analysis

CCF – Common Cause Failures

CMM – Capability Maturing Model

CM – Condition Monitoring

DMS – Decision-Making Support

DMSMS – Diminishing Manufacturing Sources and Material Shortages

EI – Economic Index

EM – Employee

EOL – Optimal End-Of-Life

EOR – Enhanced Oil Recovery

E&P – Exploration & Production

ESD – Emergency Shut Down

ETA – Event Tree Analysis

FMEA – Failure Mode and Effects Analysis

FMECA – Failure Mode, Effects and Criticality Analysis

FPSO – Floating Production Storage and Offloading Unit

FTA – Fault Tree Analysis

GHG – Greenhouse Gas

GOR – Gas-Oil Ratio

HAZOP – Hazard and Operability Studies

HSE – Health and Safety Executive

HVAC – Heating, Ventilating and Air Conditioning

IKT – Inter-Organizational Knowledge Transfer

I/O – Input/Output

IOGP – International Association of Oil and Gas Producers

LE – Life Extension

LCA – Life-Cycle Assessment

LTB – Last Time Buy

MAHs – Major Accident Hazards

MM – Middle Manager

NPV – Net Present Value

OEM – Original Equipment Manufacturer

O&M – Operation and Maintenance

OMP – Obsolescence Management Plan

P&ID – Piping and Instrumentation Diagram

PHM – Prognostic Health Management

PI – Performance Indicators

PLC – Programmable Logic Controller

PSA – Petroleum Safety Authority

PSHE – Plate and Shell Heat Exchangers

PSV – Pressure Safety Valve

RBPS – Risk Based Process Safety

RAS – Reliability, Availability, and Serviceability

ROV – Remote-Operated Vehicle

RPN – Risk Priority Number

RUL – Remaining Useful Life

SSC – System, Subsystem, or Component

SSIV – Subsea Isolation Valve

S – Severity

TDP – Touchdown Point

TG – Gas Turbines

TR – Temporary Refuge

VFF – Venting, Flaring, and Fugitive

VRU – Vapour Recovery Unit

WOR – Water-Oil Ratio

WS – Work Streams

TM – Top Manager

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INTRODUCTION

The end of life for a system, subsystem, or component (SSC) demands a decision from its operator. The operator may choose to follow the conventional approach of replacement or decommissioning or opt for life extension (LE) – a process that has attracted considerable interest across capital-intensive industries, such as oil and gas, nuclear, electrical/electronic, renewable energy, and transportation. Using this approach, the operator needs to guarantee the technical, operational, and organizational integrity of the installation throughout the extended life period (Hokstad *et al*., 2010).

In the context of the oil and gas sector, these installations include pipelines, manifolds, umbilical tubing, wells, and offshore production facilities. Many different regions are already experiencing ageing and, consequently, going through processes of life extension. Examples are: North Sea, Asia-Pacific region, China, Gulf of Mexico, Middle East, and Brazil as well. In Brazil, considering the first offshore basins developed, more than 90% of the facilities are more than 20 years old, while in the Campos basin more than 50% are (as of 2019). A similar situation is observed for subsea systems as in 2019 more than 20% of them were already operating past the life cycle contemplated in the original project.

Life extension is not merely a matter of keeping the asset operational under the same conditions or procedures for longer than originally intended, it requires a critical assessment. Extending the life of an SSC requires the implementation of additional measures to manage the risks associated with prolonged usage. This involves continuously identifying and managing new hazards that may arise over time. These measures can include revising operational procedures, increasing the frequency of inspections, and establishing redundancies in the operational control systems, among other possible actions. The complexity of these measures and the level of investment required can vary depending on the specific circumstances of each case.

In literature and among oil and gas regulations around the world, different divisions and terminologies are used to characterize three key aspects that must be considered during the life extension evaluation process: material degradation, obsolescence, and organizational issues. However, most of the focus tends to be on the physical degradation of materials (Hokstad *et al.*, 2010; Aeran *et al.*, 2017) despite the effects of ageing being far more comprehensive.

The ageing of an oil and gas facility is a multifaceted process; it is not merely defined by the chronological ageing of its SSC (Wintle *et al.*, 2006). For certain types of SSC, the primary reason for reaching the end of life is not material degradation but obsolescence. In these cases, obsolescence management must be approached comprehensively, and, in terms of scope, it cannot be limited to just technological obsolescence or issues related to SSC availability and service support from the manufacturer (Anghel *et al.*, 2003; Konoza *et al.*, 2014; Belshaw, 2015), which are the most widely recognized components of obsolescence. Instead, it needs to encompass a broader concept of obsolescence, driven by four key factors: unavailability from manufacturers and service support, new requirements or demands, technological or technical changes, and emerging conditions or needs.

In terms of organizational aspects, researchers have identified several issues that can influence the life extension (LE) decision-making process, such as workforce aging, the need for knowledge transfer, and the adaptations required due to changes in company structure (e.g., changes in ownership, organizational restructuring, mergers, and personnel reductions). In the context of the oil and gas industry, where there is an increasing trend of aging facilities being transferred from larger to smaller companies (Brandt; Bates, 2000), inter-organizational knowledge transfer becomes critical and can introduce further complexities in extending the life of these facilities. However, there is a significant gap in the literature regarding the challenges of inter-organizational knowledge transfer within the buyer-seller dyad. Specifically, there is a need to understand the mechanisms associated with knowledge transfer and the challenges faced when acquiring aging assets in the oil and gas industry by companies intending to operate them beyond their originally intended lifespan.

Furthermore, while it is known that as oil fields approach the end of their expected service life and reach depletion, both energy use and GHG emissions per unit of oil produced increase, the literature on extending asset operational life neglects GHG emissions as a crucial factor in decision-making. This factor must be added to the existing evaluation criteria of material degradation, obsolescence, and organizational issues, completing the technical evaluation of LE and incorporated into the definition of the life extension (LE) strategy and management plan.

In this sense, although many assets have reached the end of their useful life, and despite the significant benefits of life extension (LE), regulatory bodies - whether advanced in the sector or experienced with life extension - and academia developed limited material that comprehensively covers critical aspects for managing the life extension process: material degradation of the asset, obsolescence, inter-organizational knowledge transfer (IKT), and GHG emissions.

Aims and Objectives

The aim of this thesis is to provide a guideline, and a decision support tool tailored to manage the life extension process of oil and gas facilities, integrating four aspects: material degradation (physical damage), as well as issues related to obsolescence, the organization, and carbon footprint.

The main objectives of the research project are:

1) Define an approach for including a carbon footprint assessment within the evaluation of oil and gas offshore production facility life extension.
2) Provide a structured and standardized methodology (framework) for the assessment of oil and gas asset useful life extension to facilitate the analysis of ageing related issues;
3) Develop a systematic analysis based on the definition of stages to be considered in the evaluation of potential facility life extension with regards to material degradation, obsolescence and carbon footprint.
4) Advance the understanding of organizational aspects, by exploring the main constructs, challenges and safety impacts of interorganizational knowledge transfer.

These objectives seek to deliver the following benefits: (i) enable operators to more easily assess the possibility of life extension and make better-informed decisions; (ii) allow regulatory bodies to perform a more accurate evaluation of the requests received; (iii) support the development of future frameworks by managers and regulators to evaluate interorganizational knowledge transfer issues as part of oil and gas facility life extension; (iv) provide insight into managerial solutions for facilitating knowledge transfer; (v) guide other organizations in similar situations, helping them better manage the IKT process. Ultimately, these objectives seek to mitigate potential risks associated with the operation during its extended life and ensure smoother operations during and after facility transfer.

Overview and Structure of the Thesis

This thesis consists of five published or submitted papers that embody the results of the doctorate research, which were predominantly developed by the author of this thesis, with the valuable support of the co-authors and doctorate supervisors. These five papers, presented in chapters 1 to 5 (Figure 1), were accepted by or submitted to Journal of Loss Prevention in the Process Industries, Ocean Engineering, IEEE Transactions on Engineering Management and Geoenergy Science and Engineering.

Chapter 1 is based on the manuscript entitled *Guidelines for life extension process management in oil and gas facilities* and contextualizes the implementation of the life extension concept in the oil and gas industry, showing both global and Brazilian data about the subject, and presents the three areas that should be considered in the ageing process. It shows as a result a proposition of a framework consisting of twelve stages for the life extension management process. It should be noted that although the proposed framework includes the three aspects involved in ageing assessment (material degradation, obsolescence and organizational issues), it focuses primarily on the first one, addressing the others as a preliminary approach.

Chapter 2 is based on the manuscript entitled *Obsolescence management for offshore oil and gas production facility life extension* and presents the concept of obsolescence as caused by four aspects (unavailability of a product or service from manufacturers, new requirements or demands, technological or technical changes, and new conditions or needs). Additionally, it presents, as a contribution, the proposal of a framework detailing the main stages to perform the evaluation of obsolescence of the asset for which life extension is intended. This evaluation is consolidated into eight stages.

Several organizational issues can impact the life extension decision-making process. Chapter 3 investigates the knowledge transfer, particularly the inter-organizational knowledge transfer (IKT) in the context of acquiring ageing assets by a company that intends to operate them beyond their useful life. It is based on the manuscript entitled *Challenges in inter-organizational knowledge transfer for the life extension of oil and gas facilities*. It presents the elements and mechanisms associated with IKT and the respective challenges of this process to support the development of future frameworks by managers and regulators and to provide insight into managerial solutions for facilitating knowledge transfer.

Chapter 4, based on the manuscript entitled *Investigating the Impacts of Knowledge Transfer Between Oil and Gas Companies on Process Safety*, delves deeper into IKT considering the gap of research on knowledge transfer in the context of facility acquisition. It identifies potential consequences of unsuccessful IKT for process safety when an asset is acquired, and no personnel is transferred. Based on the findings identified in two different environment, onshore and offshore, practical guidelines for improving IKT are suggested for each stage of the transfer.

Chapter 5, based on the manuscript entitled *Introduction of a Carbon Footprint Assessment in the Oil and Gas Facility Life Extension Decision-Making Proc*ess, expands the three aspects involved in ageing assessment presented in Chapter 1, and proposes the inclusion of a carbon footprint assessment within the evaluation of oil and gas offshore production facility life extension, adding an environmental lens to the decision-making process of oil and gas facility life extension. In this sense, the chapter proposes an eleven-stage framework to systematize the ageing related carbon footprint assessment and support life extension.

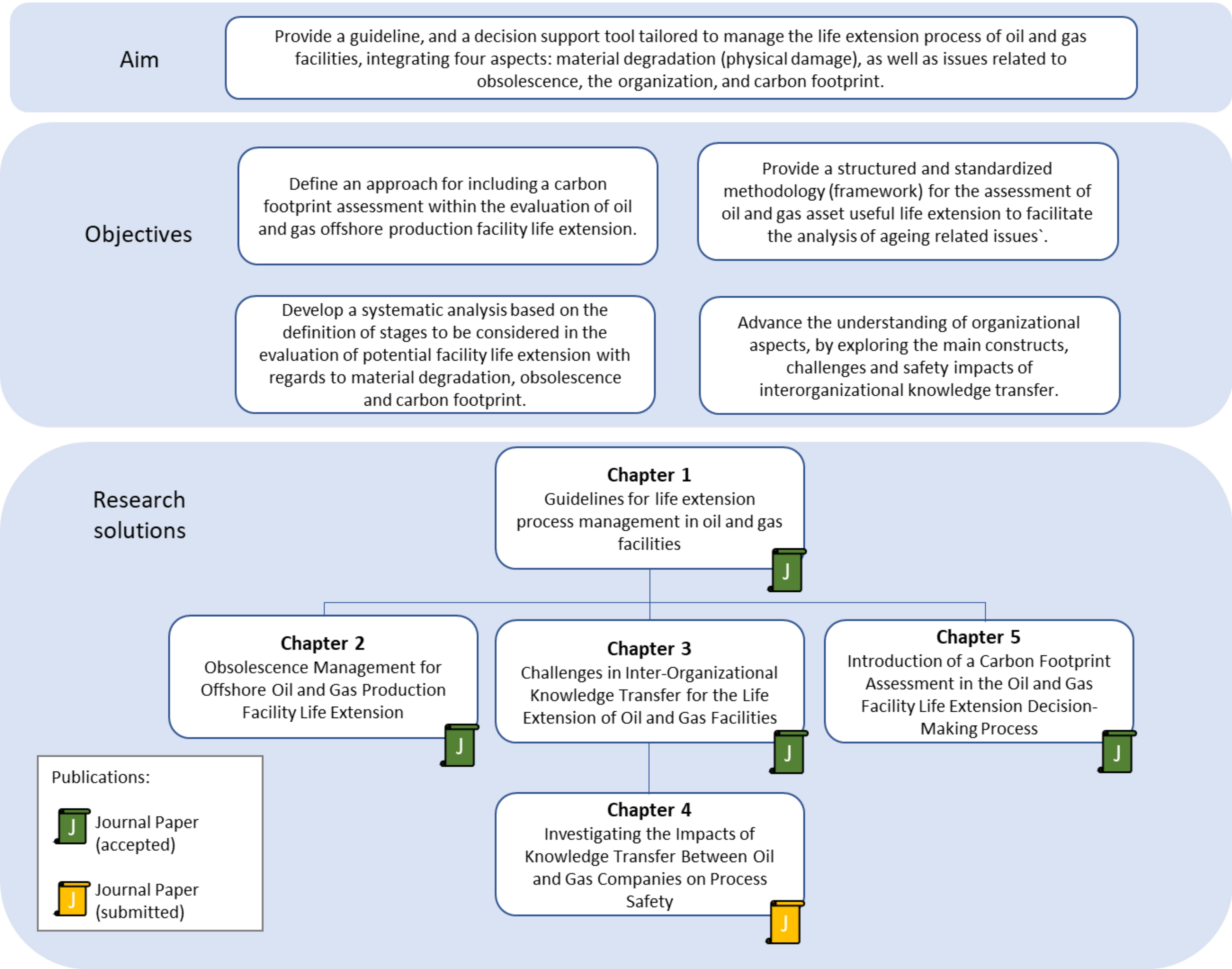
In this context, the objectives outlined in the "Aims and Objectives" section are achieved as follows: objective 1 is addressed in Chapter 5; objective 2 is covered in Chapter 1; objective 3 is explored across Chapters 1, 2, and 5; and objective 4 is discussed in Chapters 3 and 4.

It is important to note that Chapters 2, 3, and 5 provide a deeper exploration and further detailing of Stage 6 of the proposed framework presented in Chapter 1. In this regard, while the findings of these chapters impact the subsequent stages of the framework, these stages fall outside the scope of these Chapters. Specifically, the stages that are not covered include: the assessment of economic issues, the definition of a Life Extension (LE) Management Plan, obtaining regulatory approval, the implementation of the LE Management Plan, and the monitoring of its effectiveness.

All the articles presented in Chapters 1, 2, and 5, which aimed to propose frameworks for evaluating the aspects of material degradation, obsolescence, and carbon footprint within the context of facility life extension decision-making, did not seek to develop each proposed stage of the framework in detail. Instead, their goal was to consolidate the stages, which are presented in the literature in an unstructured way, into a coherent methodology (framework) for evaluating the topic under consideration. Additionally, these articles include case studies to validate the application of the proposed framework, using data and a combination of information from real platforms operating in Brazil, including the subsea system and equipment of the utility and process plant.

Similarly, in the case of chapters 3 and 4 a qualitative case study was conducted in which an offshore facility was transferred from one company to another, without the personnel from the original company being transferred to the destination company.

Figure 1 - Structure of the Thesis



Source: The author, 2024.

Publications Related to Thesis Research

As previously mentioned, the contributions of this research have been disseminated in published format. The published works are listed below in chronological order:

FERREIRA, N. N. et.al. Guidelines for life extension process management in oil and gas facilities. *Journal of Loss Prevention in the Process Industries*, v. 68, 2020. DOI: 10.1016/j.jlp.2020.104290.

FERREIRA, N. N. et. al. Obsolescence management for offshore oil and gas production facility life extension. *Ocean Engineering*, v. 285, 2023. DOI: 10.1016/j.oceaneng.2023.115388.

FERREIRA, N. N. et. al. Challenges in inter-organizational knowledge transfer for the life extension of oil and gas facilities. *IEEE Transactions on Engineering Management*, p. 1–17, 2024. DOI: 10.1109/TEM.2024.3361797

FERREIRA, N. N. et al. Investigating the Impacts of Knowledge Transfer Between Oil and Gas Companies on Process Safety. *IEEE Transactions on Engineering Management* (submitted).

FERREIRA, N. N. et. al. Introduction of a Carbon Footprint Assessment in the Oil and Gas Facility Life Extension Decision-Making Process. *Geoenergy Science and Engineering*, v. 240, 2024. DOI: 10.1016/j.geoen.2024.213032

As primary author, I wrote the papers listed above, and performed the research as well as analysis presented in them. The co-authors are either my PhD thesis supervisor, Prof. Marcelo Martins, Gaya Figueiredo and Prof.ª Rebecca Dziedzic, or collaborators from other institutions, Prof.ª Ana Burchaarth, Carmen Migueles and Shannon Lloyd, Prof. Cyro Albuquerque, Silvio de Oliveira Junior and Victor Gagno. The co-authors provided ideas and insights, proofread and edited the manuscripts before submission. I have received permission and endorsement from them to include in this document all materials listed above.

1. GUIDELINES FOR LIFE EXTENSION PROCESS MANAGEMENT IN OIL AND GAS FACILITIES

Facilities life extension has caught the attention among the capital-intensive industries, like oil and gas. By extending the life cycle of the industrial assets, a wide range of benefits is obtained, comparing with other life ending management strategies. This article first contextualizes the implementation of the life extension concept in the oil and gas industry, showing global data about life extension. Despite the importance of the ageing process, due to its great economic impact and the risk it poses to the production sector, regulatory entities, even in countries more advanced in that sector or that have already experienced the extension process, developed only superficial material about the topic without defining a structured methodology for the assessment of the possibility of useful life extension. The available references do not allow a comprehensive analysis of that possibility, which highlights the importance the methodology proposed. Thus, this article proposes a guideline for the life extension process management, strengthening a framework containing the main evaluation stages, aiming to facilitate the analysis of issues related to ageing and to support the decision-making process. Lastly, real case studies regarding current life extension processes submitted to the Brazilian regulatory body were evaluated against the proposed framework stages, evidencing their lack of necessary details to support the decision-making. Upon the realization that the real cases identified do not allow for the assessment of the contribution and adequacy of the proposed framework in its entirety, the same was also applied to a hypothetical case. The latter was developed based on facts reported by a major operator in Brazil. The result was the determination that the use of the proposed methodology transformed the assessment of the possibility of life extension into a systematic and transparent process, leading to easier and better-founded decision-making procedures, and improving the management of the asset during its extended life.

1.1 Introduction

The end of the life cycle of a system, subsystem or component (SSC) requires a decision from its operator. As traditional alternatives, the replacement of such equipment by a similar one or its decommissioning can be mentioned. The latter approach is usually taken when the equipment expected production does not pay off its replacement. Another alternative that has caught great attention, mainly from the capital-intensive industry, consists in SSC life extension. This is, indeed, a possibility provided that technical, operational and organizational integrity is assured (Hokstad *et al.*, 2010).

The SSC life extension process cannot be mistaken with keeping the asset in operation for a period longer than that foreseen under the same conditions or the same operational procedures established in the project, without any changes in the operational strategy or added effort. The concept behind this process is the critical assessment of the asset as regards materials degradation and obsolescence or assets technological ageing, besides the need of the organizational issues assessment, also named organizational ageing. The life extesion (LE) process includes recognizing and managing new hazards that might appear due to lengthy asset operation, and thus includes the definition of added measures to control the associated risks. The added measures may vary in implementation complexity and in the amount of investment needed, and it can go from establishing new operational procedures, increased inspection frequency until new redundancies are defined for the added operational control system, among other possible contingency measures.

In this context, Shafiee and Animah (2017) quote the benefits of the LE approach in four different areas: economic, technical, social and environmental.

Aeran *et al.* (2017) state that in the last two decades, there was a significant effort to study ageing assets and the associated mechanism of failures; because of this effort, guideline development initiatives and models to back up LE have increased. Shafiee and Animah (2017) try to quantify this tendency and, based on the data collection of publications related to LE made between the years of 1986 and 2015, proving that, in the last few years, the concept has been growing in relevance in a variety of industries.

Indeed, it is a concept applied to a wide range of industrial assets, such as those of the oil and gas, nuclear, electric/electronic, renewable energy, transport, among other industries. As an example, plants in the nuclear industry can be mentioned; they began to operate with a 30 to 40-year license; however, until 2011, 60 licenses had been granted to the United States alone, so that they could operate for as long as 40–60 years.

The LE approach in the exploration and production of oil and gas comprises different types of facilities, namely: pipelines, wells, manifolds, umbilical tubing, offshore production facilities, rigs and vessels (Shafiee; Animah, 2017).

In the international context of the oil and gas sector, according to Ersdal, Sharp and Stacey (2019), more specifically in the North Sea, approximately 2/3 of the infrastructure can be considered ageing and in the LE phase. Therefore, the United Kingdom and Norway regulatory agencies currently have LE as one of their main focus.

The Health and Safety Executive (HSE), the United Kingdom's regulatory body, started Key Programme 4 in July 2010; the final report was published in 2014. In this report, half the country's fixed platforms were verified to be close to the end or had reached the end of their expected life cycle (Health and Safety Executive, 2014).

The situation in Norway is similar to that of the United Kingdom. Ersdal, Hornlund and Spilde (2011) states that the agenda of the Norwegian regulatory agency, Petroleum Safety Authority (PSA), has the ageing and LE issues included as a priority since 2002. In 2005, these issues became key aspects to the agency, with the institution of a program, the main activities of which aimed to increase the knowledge about ageing implications, especially in the LE phase.

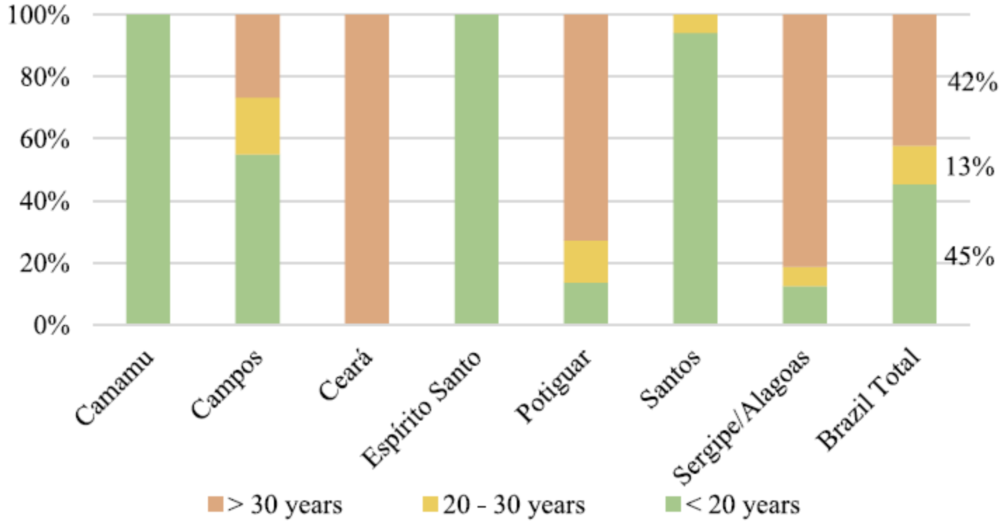
Zawawi, Liew and Na (2012) state that the situation is similar in the Asia-Pacific region. In Malaysia, the authors say that 48% of the platforms had exceeded the designed 25-year life cycle in 2012. According to Liu *et al.* (2015), the scenario in China, regarding production platforms ageing, follows those in other countries. The first offshore production platform of the country reached the end of its designed life cycle in 2005 and was still operating in 2014.

Regarding the data on the Middle East, Aeran *et al.* (2017) state that the percentage in this region is higher, for 70%, of a total of 800 platforms, already operate beyond their life cycle.

In the Gulf of Mexico, Kaiser and Liu (2018) indicate that between 27 and 51 structures that operate in deep waters will reach the end of their designed life cycle until 2031 and between 12 and 25 decommissioning are expected between 2017 and 2022.

In the Brazilian case specifically, based on data from its regulatory body (Brazilian National Agency of Petroleum, Natural Gas and Biofuels - ANP), the Brazilian platforms in operation have age characteristics as shown in Figure 1.1.

Figure 1.1 - Age of Brazilian platforms in operation



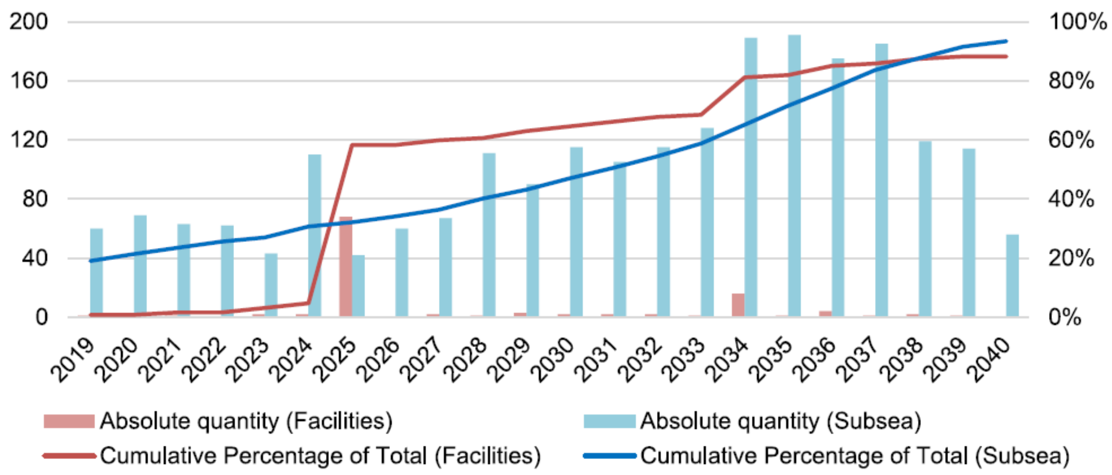
Source: ANP, 2019

The first offshore basins developed in Brazil, Sergipe/Alagoas, Ceará and Potiguar, had their peak in the seventies; most of their platforms have been built over 30 years ago. For these facilities to continue operating, LE studies must be conducted to keep their operations for more 20 years.

In turn, the Campos basin, which had its peak in the eighties and nineties, has a more balanced situation. 20% of its platforms are near the end of their life cycle and approximately 25% have operated for over 30 years, which indicates that about half of all the facilities in the basin has shown or will very soon show studies to back up the operations of these facilities beyond their designed life cycle, in case the licensee intends to continue producing with those assets.

Based on data from ANP, the predicted number of Brazilian platforms and subsea systems that will reach the end of their life cycle is shown in Figure 1.2. The graph reveals only the tendency, not considering the facilities decommissioned before 2019 and does not consider future commissioning.

Figure 1.2 - Number of facilities and subsea systems at the end of their life cycle until 2040



Source: ANP, 2019

Among the Brazilian platforms currently operating, 53% will reach the end of their life cycle in 2025, which represents a great challenge to the Brazilian industry, regardless of whether the operators choose to decommission or develop a LE plan.

As well as the topside, the subsea systems also represent an ageing challenge to the Brazilian industry, given that approximately 4% of the systems will reach the end of their life cycle in 2020. Moreover, the importance of discussing LE is urgent, for, in 2019, 17% of the subsea systems were already operating beyond the life cycle originally established.

However, despite the importance, the great economic impact and the risk posed to the oil and natural gas production sector, there is not, in the Brazilian regulatory framework, a structured methodology for assessing the possibility of extending the useful life of a facility, specifically a methodology that would: (i) establish the points to be evaluated; (ii) define how to evaluate them in an integrated manner; (iii) assist the regulatory body in the evaluation of the requests received, and (iv) make it possible to monitor the facilities that had their life period extended. The need for a methodology encompassing the aspects mentioned above becomes evident from the deficiencies observed in the processes that were submitted to the Brazilian regulatory agency, as it will be detailed in the case study section of this article.

Regarding the regulatory bodies in other countries, even those that are more developed in the sector or that have already experienced the extension process, according to the best knowledge of the authors, little material addresses the topic, and still only in a superficial manner.

In short, a guideline with a standardized definition of the aspects to be considered for the evaluation of the possibility of extending the life of a facility could, on the part of the operators, make the systematization of analyses easier and contribute to better management over the extended life period. As a result, the risk associated with the operation could be minimized and operational efficiency improved. On the other hand, the guideline could assist the regulatory body in performing a more accurate evaluation of the requests received.

It should be noted that the purpose of the article is not the development of each specific step pointed out in the framework, since each topic is been addressed individually in the literature by several authors with an interesting level of depth (Petroleum Safety Authority, 2005; Jardine; Lin; Banjevic, 2006; Franklin *et al.*, 2008; Hokstad *et al.*, 2010; Sharp; Terry; Wintle, 2011; Vaidya; Rausand, 2011; Nitoi *et al.*, 2011; Hornlund *et al.*, 2011; Ersdal; Sharp; Galbraith, 2014; Carvalho *et al.*, 2015; Liu *et al.*, 2015; Shafiee; Animah; Simms, 2016; Aeran *et al.*, 2017; Marques; Silva, 2017; NOrwegian Oil and Gas Association, 2017; Animah and Shafiee, 2018).

However, the topics covered in isolation, although absolutely relevant, do not allow an accurate analysis, or even minimally adequate, of the possibility of extending the life of an asset, attesting the importance of proposing a structured analysis methodology.

In this sense, the focus of the article is to take this set of topics, which is presented in the literature in an unstructured way, and consolidate it in stages, proposing a methodology (framework) for the development of the management process of useful LE in a broad and systematic way. Additionally, the article presents a theoretical foundation based on the literature available for each of the stages of the proposed methodology.

Thus, from a scientific viewpoint, it is understood that the greatest contribution and innovation of the article consists of integrating the LE process in a guideline not presented by any of the articles individually.

To achieve the aforementioned objective, the categorization proposed by different authors regarding the ageing process and the importance of ageing management is discussed. The article, then, proposes a framework for the useful LE process, describing the main stages that make up this process. The importance of structuring the process in stages is highlighted by the presentation of three case studies that make a comparative evaluation between the documents related to the LE processes underway in Brazil submitted to ANP and the stages proposed in this article.

Considering the gaps in the real cases in terms of organization, completeness and scope, the methodology described in this article was applied to a hypothetical case, based on facts reported by a major operator in Brazil. Finally, the conclusions of the work are presented.

1.2 Theoretical background

Although the LE of industrial assets can result in long-term economic benefits, the SSC integrity condition can be unsuitable for extended operations when assessed under environmental or safety perspectives (Shafiee; Animah; Simms, 2016). Safety commitment and environmental impacts during the extended life period may result in significant damages to the operator, which may cause the revocation of the operator's extended operation license, original license suspension, fines and harm to the company's reputation (Shafiee; Animah, 2017).

Ageing process management is not all but an essential part of the integrity and process safety management of assets that will operate beyond their designed life cycle. This management includes activities and decisions that will allow identifying ageing potential threats in the first stages, so that they can be prevented or mitigated (Sharp; Terry; Wintle, 2011).

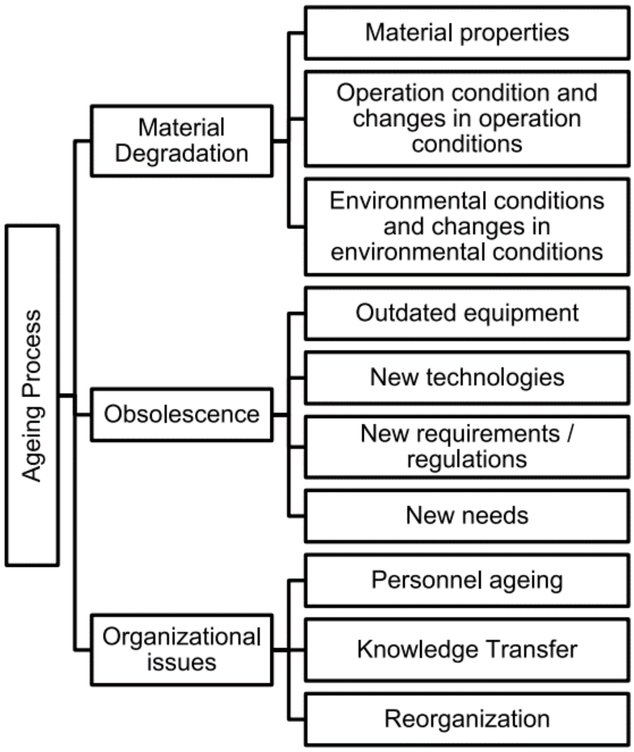
The ageing process has been categorized in different ways. Petroleum Safety Authority (2005), Hornlund *et al.* (2011), and Ersdal, Sharp and Galbraith (2014) categorize this process into functional ageing, technological ageing, knowledge-based ageing and organizational ageing.

Functional ageing includes problems of material degradation, along with problems related to weariness, corrosion or any type of physical damage. The first two types of degradation are considered the main causes of failures in offshore facilities, since they account for reducing the structural integrity of the facilities and cause tension concentration (Guedes Soares; Garbatov, 1998; Stacey; Birkinshaw; Sharp, 2008; Popoola *et al.*, 2013; Adasooriya; Siriwardane, 2014).

Technological ageing can refer to the old standards and regulations that are no longer considered enough to maintain safety. Knowledge-based ageing, conversely, can occur when the original documentation of the project is outdated due to the availability of new knowledge, such as new analysis methods, new models, new standards, etc. Finally, organizational ageing is the personnel ageing and the insufficiency of competence to cope with the facility.

In a similar way, Hokstad *et al.* (2010) separate the ageing process into three main areas: (i) material degradation (physical damage), (ii) obsolescence, which includes the operation and outdated technology in the facility, and (iii) the issues related to the organization, as shown in Figure 1.3. According to these authors, the operator should ensure the technical, operational and organizational integrity of the facility during its LE period.

Figure 1.3 - Aspects of ageing management



Source: Based on Hokstad *et al.*, 2010

Most of the literature focus on material physical degradation, but the obsolescence aspects and the organizational issues mentioned above also represent essential changes in ageing management (Hokstad *et al.*, 2010; Aeran *et al.*, 2017).

In the facilities LE process, each aforementioned aspect shows its own set of challenges that must be identified, plus measures to cope with these challenges. The challenges are identified at different "levels". While the material degradation is evaluated at component, equipment and system levels, the organizational issues are mostly evaluated at a system or even facility level. In the same way, obsolescence is most often addressed at system level (Hokstad *et al.*, 2010).

Material degradation includes understanding degradation mechanisms and the material failure mode. Hence, to evaluate the equipment condition, some information/parameters are essential, given that they influence the degradation process: process parameters and environmental aspects.

Obsolescence involves the following challenges (Hokstad *et al.*, 2010):

(i) outdated equipment usually results in the unavailability of spare parts and services, which can demand the implementation of an operation philosophy and distinctive maintenance.

(ii) possibility/need of new technologies during the extended life period and the need of evaluating the consequences of the combination.

(iii) regarding the requirements and regulations, at the end of the facilities life cycle, these may have been reviewed and new performance standards may have been established. Typical examples are new requirements related to the environment, new operational safety requirements and new technical requirements for equipment. During a facility LE period, the latest reviews of the regulations and performance standards must be followed, at least for the SSC that can impact safety.

(iv) new needs can come up due to new operational and/or production conditions or the need to increase the effectiveness during the LE period. These new conditions must be identified and the risk impacts must be managed.

The issues related to the organization involve human factors and issues from the organization itself, such as the following challenges:

(i) maintaining of personnel competence (workforce ageing). Maintaining trained and qualified workforce with knowledge about ageing equipment and the loss of knowledge due to retirement are important factors to be considered for facilities LE. Considering this, for competence maintenance, it is necessary to keep records within the organization, so that losing a person does not disproportionally harm the operational capability of the organization.

(ii) knowledge transfer during the LE period.

(iii) possibility of the organization reorganization, such as company's property transfer, organizational structural changes, merging with other companies.

Furthermore, other changes may result in new challenges to the facility that undergoes a LE process, namely: new types of operation (for example, Integrated Operations), automation of the operations resulting in personnel cutback, among other changes.

The authors highlight that obsolescence and organizational issues are associated, given that, for example, a new technology may require a new set of skills from the operators (Hokstad *et al.*, 2010).

Based on the authors mentioned, this article opted for adopting the categorization proposed by Hokstad *et al.* (2010), since this approach, besides being very didactic, uses common oil and gas sector language, providing examples of each category and raising some questions that must be evaluated to fully understand each ageing aspect.

Among other detailed aspects that will be presented in the next section of the article, the successful implementation of a LE management plan for facilities depends on understanding the degradation process, the availability of data regarding the assets real condition, reliable evaluation methods and the implementation strategy to address the growing risk of failure over time (Kancev; Gjorgiev; Cepin, 2011; Kancev; Cepin, 2011; Gran *et al.*, 2012).

Franklin *et al.* (2008) concluded it is important to evaluate from a common approach so that operators can demonstrate the assets safety during LE and promote lessons learned for future analyses. Corroborating this idea, Matteson (2014) adds that establishing a structured process can be very useful to help the companies and regulatory authorities to guarantee a continuous operation of these facilities beyond the designed life cycle.

With the objective of structuring a methodology for the management of an asset's useful LE, after the consolidation of stages the academic literature as well as international regulatory standards were searched for works that addressed any of the stages related to this process.

Franklin *et al.* (2008), Shafiee, Animah and Simms (2016) and the Norwegian Oil and Gas Association (2017) brought the greatest contributions in terms of the number of stages included in the framework, which is presented in the next section of this work. The authors approach the topic in a comprehensive manner, with Franklin *et al.* (2008) providing the greatest contributions in the preliminary stages of the framework, Shafiee *et al.* (2016) in the intermediate stages and Norwegian Oil and Gas Association (2017) in the final stages.

In the same sense, Hokstad *et al.* (2010), Liu *et al.* (2015) and Animah and Shafiee (2018) brought a contribution to the work of a medium degree, and finally the authors

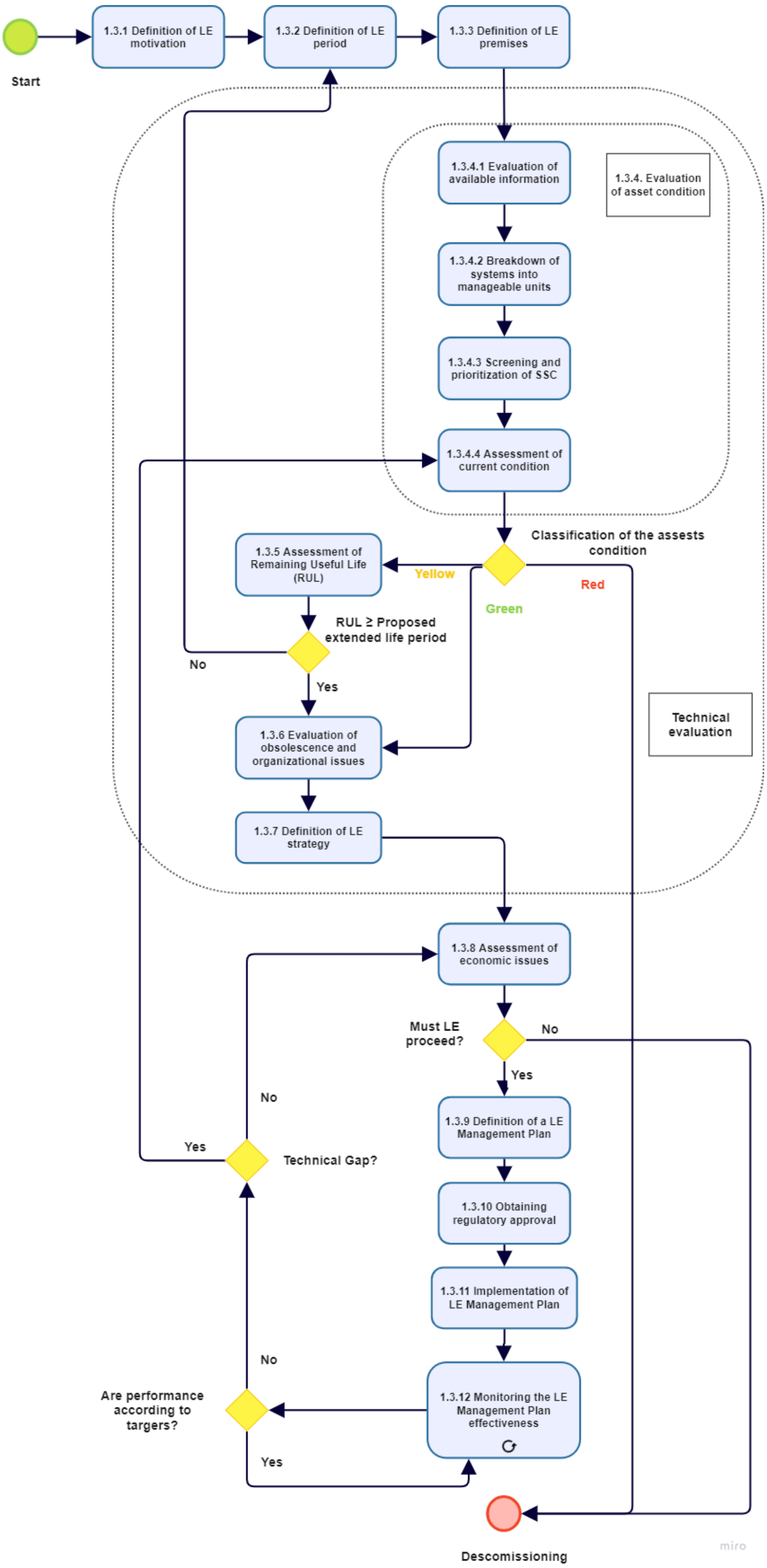
Petroleum Safety Authority (2005), Jardine, Lin and Banjevic (2006), Hornlund *et al.* (2011), Nitoi *et al.* (2011), Sharp, Terry and Wintle (2011), Vaidya and Rausand (2011), Ersdal, Hornlund and Spilde (2011), Carvalho *et al.* (2015) and Aeran *et al.* (2017) contributed to a smaller number of stages when compared to the other works cited. However, it is noteworthy that, although these contributed with only one or two stages for the definition of the framework, that contribution was decisive because they were unique in some steps.

The focus of the article is to consolidate this set of topics in stages, proposing a methodology (framework) for the development of a process for the management of the useful LE in a broad and systematic way, as discussed in the next section.

1.3 Guidelines proposed for life extension process management in oil and gas facilities

Based on the contribution of the authors previously mentioned for evaluating specific parts of the ageing process, a guideline for LE process management are proposed, consolidating the main evaluation stages in a framework shown in Figure 1.4 with each step summarized in Table 1.1.

Figure 1.4 - Life Extension Management Process flow chart



Source: The author, 2024

Table 1.1 - Life Extension Process Management stages

Item	Stages	Summary/Description	References
1.3.1	Definition of LE motivation	Definition of the reason to consider LE of SSC	Franklin *et al.* (2008).
1.3.2	Definition of LE period	Definition of the desired LE period. Based on this definition, the level of detail required for the LE process is assessed.	Franklin *et al.* (2008).
1.3.3	Definition of LE premises	Definition of the assumptions (objective and scope) of the LE plan, considering the proposed LE period.	Shafiee, Animah and Simms (2016).
1.3.4	Evaluation of asset condition	Survey of SSC current condition data, regarding integrity, to assess the material degradation condition. This assessment is made through four main stages, according to items 3.4.1 to 3.4.4.	Petroleum Safety Authority (2005); Franklin *et al.* (2008); Shafiee, Animah and Simms (2016).
1.3.4.1	Evaluation of available information	Data compilation to identify the level of detail of available information.	Petroleum Safety Authority (2005); Franklin *et al.* (2008); Hokstad *et al.* (2010); Carvalho *et al.* (2015); Liu *et al.* (2015).
1.3.4.2	Breakdown of systems into manageable units	Splitting a complex system into subsystems and components to facilitate the assessment of the condition and to provide the concentration of efforts.	Petroleum Safety Authority (2005); Liu *et al.* (2015); Shafiee, Animah and Simms (2016); Animah and Shafiee (2018).
1.3.4.3	Screening and prioritization of SSC	Selection of safety critical elements (SCE) to allocate resources to SSC whose functions are more critical in terms of safety. This guarantees improvement in reliability, reduced associated risks and increased productivity of equipment and processes.	Hokstad *et al.* (2010); Sharp, Terry and Wintle (2011); Nitoi *et al.* (2011); Carvalho *et al.* (2015); Shafiee, Animah and Simms (2016); Animah and Shafiee (2018).
1.3.4.4	Assessment of current condition	Technical assessment of the SSC physical and functional (health) conditions.	Petroleum Safety Authority (2005); Franklin *et al.* (2008); Liu *et al.* (2015); Shafiee, Animah and Simms (2016); Animah and Shafiee (2018).
1.3.5	Assessment of Remaining Useful Life (RUL)	Estimate of SSC remaining life. This estimation is based on data collection, evaluating failure mechanisms, selecting the estimated RUL model and comparing RUL and proposed LE period (item 3.2).	Vaidya and Rausand (2011); Jardine, Lin and Banjevic (2016); Shafiee, Animah and Simms (2016); Aeran *et al.* (2017); Animah and Shafiee (2018).
1.3.6	Evaluation of obsolescence and organizational	The assessment involves: outdated equipment issues, new technologies introduction, new requirements and/or new regulations and new needs, as well as personnel ageing, knowledge transfer and reorganization.	Petroleum Safety Authority (2005); Hokstad *et al.* (2010); Hornlund *et al.* (2011); Ersdal, Sharp and Galbraith (2014).

Item	Stages	Summary/Description	References
	issues		
1.3.7	Definition of LE strategy	Establishment of LE strategy to be applied to each SSC.	Franklin *et al.* (2008); Shafiee, Animah and Simms (2016).
1.3.8	Assessment of economic issues	The assessment using an economic index (EI) based on the evaluation of the cost/benefits associated with LE, which considers factors such as increased production, improvement in safety, delayed decommissioning costs, capital cost, installation cost and operating expenditures.	Petroleum Safety Authority (2005); Shafiee, Animah and Simms (2016).
1.3.9	Definition of a LE Management Plan	Elaboration of LE management plan, containing at least the following aspects: definition of LE strategy; definition of an inspection, test and maintenance program; specifications of indicators, planning of spare parts, general vision, premises and limitations of the decisions made over the LE strategy definition process; identification of specific procedures to be implemented in the extended life period and identification of risk reducing mitigating measures.	Petroleum Safety Authority (2005); Franklin *et al.* (2008); Hokstad *et al.* (2010).
1.3.10	Obtaining regulatory approval	Regulatory body verification of the documentation submitted by the operator, evaluating the consistency of the LE Management Plan to the current regulations and sector standards.	Petroleum Safety Authority (2005); Shafiee, Animah and Simms (2016).
1.3.11	Implementation of LE Management Plan	Considering the global risk scenario evaluation within the acceptable limits, the implementation of LE planning guarantees the technical, operational and organizational level of the facility during the extended life period.	Petroleum Safety Authority (2005); Shafiee, Animah and Simms (2016).
1.3.12	Monitoring the LE Management Plan effectiveness	The continuous evaluation of the Plan effectiveness to verify the maturity level of the organization regarding ageing effects and SCE management effectiveness.	Petroleum Safety Authority (2005); Sharp, Terry and Wintle (2011).

Source: The author, 2024

The proposed framework is comprised of twelve stages detailed and subcategorized in a set of activities: (i) definition of LE motivation; (ii) definition of LE period; (iii) definition of LE premises; (iv) evaluation of asset condition; (v) assessment of Remaining Useful Life (RUL); (vi) evaluation of obsolescence and organizational issues; (vii) definition of LE strategy; (viii) assessment of economic issues; (ix) definition of a LE Management Plan; (x) obtaining regulatory approval; (xi) implementation of LE Management Plan and (xii) monitoring the LE Management Plan effectiveness.

The stages (iv), (v), (vi) e (vi) comprise what can be considered the technical evaluation of the LE. The stage (iv), in turn, is subdivided into four different steps: evaluation of available information, breakdown of systems into manageable units, screening and prioritization of SSC and assessment of current condition.

Depending on the outcome of the stage (iv), the decision can be made in three different ways:

- perform the decommissioning of the asset, that is, do not proceed with the life extension process due to the impossibility of the SSC in terms of material degradation.
- proceed to stage (v), in which the RUL must be calculated and verified if it is compatible with the defined period in the stage (ii) for the life extension.
    - If they are compatible, proceed to stages (vi) and (vii) of the flowchart related to the evaluation of obsolescence and organizational issues and the LE strategy.
    - Otherwise, there will be a need to reassess the intended extension period, returning to stage (ii).
- proceed to other technical approaches (obsolescence and organizational issues), according to stages (vi) and (vii) of the flowchart.

After the technical evaluation (stage iv) is concluded, we proceed to the other stages of the LE evaluation process.

Based on the results obtained in the stage (viii), assessment of economic issues, it is evaluated whether it is economically feasible to continue with the LE process or whether to decommission the asset.

When considered economically feasible, we proceed to the next stages in the process: (ix) definition of a LE Management Plan; (x) obtaining regulatory approval; (xi) implementation of LE Management Plan and (xii) monitoring the LE Management Plan effectiveness.

From stage (xii), it is assessed whether the asset is performing as expected in the LE Management Plan, identifying which aspects are compromising the Plan's effectiveness and returning the respective stages of the flowchart (technical or economic) to reassess the issue.

The scope of each stage of the proposed framework is detailed in the next subsections. Table 1.1 indicates the subsection of the paper in which each stage will be deeply discussed, besides listing the references that contribute to identifying the importance of each stage of the framework.

1.3.1 Definition of LE motivation

According to Franklin *et al.* (2008), the triggers that motivated the facilities' life extension, often resulting from property changes or capital financing, usually consists in: (i) field life extension, beyond the one previously proposed; (ii) tubing connections that reached the end of life cycle and that will be connected to pipeline systems that were recently installed; (iii) operation change or submission of loads not covered by the project safety envelope; (iv) process or design conditions modification or changes in the way of using the equipment, for example, when it comes to pipes, that begin to transport products which are different from the ones previously established.

1.3.2 Definition of LE period

Considering LE motivation, the period of interest should be established and/or the need for which the possibility of extension will be evaluated. This is because the level of detail of the evaluation may vary according to the proposed extension period.

Thereby, for a short LE period (between 1 and 3 years), an initial qualitative evaluation could be enough. If this evaluation is not conclusive, a full quantitative evaluation would be necessary. Conversely, for long LE periods, not only qualitative would usually be necessary but also quantitative evaluations.

1.3.3 Definition of LE premises

In the LE Management Process, the objectives must be established clearly, and fit the stakeholders' requirements for the extended operation of assets. Stakeholders for a LE project include regulators, asset operators and investors (Shafiee; Animah; Simms, 2016).

In most industries, the main objective of the LE process is to increase the level of production and, thus, the revenue performance (Shafiee; Animah; Simms, 2016).

At this stage, the scope of the program should also be defined, establishing its coverage, regarding SSC, for the following studies.

1.3.4 Evaluation of asset condition

Considering the three areas proposed by Hokstad *et al.* (2010) regarding the ageing process, as presented in section 1.3 of this article, the evaluation of asset condition refers to the material degradation evaluation; the other areas (obsolescence and organizational issues) are shown in item 1.3.6.

Hence, SSC integrity can be assessed in a quantitative way, by means of experimental laboratory procedures, prognostic health management (PHM), Bayesian Network, Failure Mode, Effects and Criticality Analysis (FMECA), Finite Element Method, virtual age reduction model, Arrhenius equation. A qualitative assessment can also be performed, such as: visual examination, qualitative risk assessment, gap analysis, specialists' opinion, among others.

The asset condition evaluation stage can be divided into four main activities: (i) evaluation of available information; (ii) breakdown of systems into manageable units; (iii) screening and prioritization of SSC; and (iv) assessment of current condition. These activities are detailed in the following subitems.

1.3.4.1 Evaluation of available information

In order to evaluate the asset condition in the facility LE process, the data must first be compiled (FRANKLIN *et al.*, 2008). This compilation aims to identify the detail level of the information available.

According to Liu *et al.* (2015), the lack of reliable data may affect the assessment and the LE decision-making process. Franklin *et al.* (2008) add that the mere fact that the operator has insufficient data makes it be compulsorily assessed and, due to this limitation, the corrective actions must be identified and implemented.

Carvalho *et al.* (2015) establish the need to survey/assess the following data:

(i) project data, including basic field data, such as field flow chart, field layout, list of equipment materials, equipment manuals, project premises.

(ii) historical parameters of the field operation (operational parameters), such as temperature, pressure, sand flow, basic sediments and water (BSW), H_2S and CO_2 concentration, among others. During this stage, the behavior of the historical data shall be tracked through the verification of the maximum and average values.

(iii) data from equipment inspections, maintenance, intervention, and field changes.

Complementarily, Hokstad *et al.* (2010) highlight that data from failures and challenges related to integrity and material degradation should be gathered. Additionally, they point out the need of information regarding (i) availability to inspect and monitor the SSC to obtain knowledge about its current situation and (ii) SSC accessibility for maintenance and/or modification.

Liu *et al.* (2015) introduce the need of enhanced monitoring in order to assess and to ensure the asset integrity during the extended life and synthetize the data set considered to be essential to the LE process in several stages of the facility life cycle, according to Table 1.2.

Table 1.2 - Critical information for the life extension process

Life Cycle Stage	Information
Design/ Installation	Material(s), protection, insulation Process definition and design criteria Equipment specifications Design codes and standards Design drawings

Life Cycle Stage	Information
	Design life calculations Operation and process info Installation load Installation accidents As-installed/built documentation Technical and engineering queries and variations Close-out and certification packs Design records required for final decommissioning planning
Operation	Information about maintenance and modification Process/Operation parameters Info. from condition monitoring Info. from inspection/testing Info. from similar operation New standards and recommended practice New tools/design methods/experience from design Repairs performed Investigation/reports of accidents and incidents and influence on structures strength Information from similar operations
Life extension	Information about planned maintenance and modification Future process/operation parameters Changes in classification due to change in operation parameter Length of LE period Future capabilities to monitor, access, operate and maintain the SSC Planned operational changes that imply new needs and load increase Future crew situation

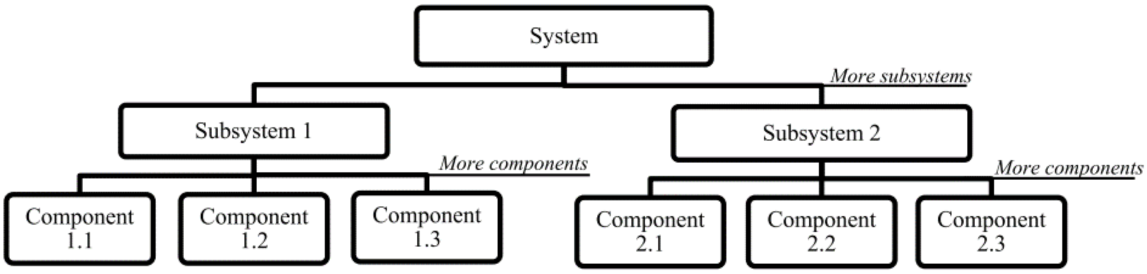
Source: Based on Liu *et al.*, 2015; Hokstad *et al.*, 2010

1.3.4.2 Breakdown of systems into manageable units

Khan and Haddara (2004), Krishnasam, Khan and Haddara (2005) and Haddara, Khan and Krishnasamy (2008) showed that splitting a complex system into manageable units facilitates the decision makers to focus on the subsystems and components whose failures might substantially affect the system availability, result in economic loss, compromise safety and generate environmental impacts.

Similarly, considering that the evaluation methods of the different types of SSC are different and that the resources should be concentrated on those with greater impact in safety (Liu *et al.*, 2015; Shafiee; Animah; Simms, 2016; Animah; Shafiee, 2018), the equipment breakdown should be executed, according to Figure 1.5.

Figure 1.5 - System breakdown structure



Source: Based on Liu *et al.*, 2015; Shafiee; Animah; Simms, 2016; Animah; Shafiee, 2018

Figure 1.5 brings the breakdown into three levels, but the number of levels varies according to the need and complexity of the analysis. The breakdown of complex systems into subsystems and components aims to facilitate the analysis and to identify common cause failures (CCF). For example, a common cause failure of multiple components can lead to a subsystem failure.

1.3.4.3 Screening and prioritization of SSC

After the breakdown of the systems into manageable units, it is necessary to identify and to prioritize the SSC.

During the LE process, the resources available (financial, workforce, material and technological) should mainly be allocated to components whose failure could result in severe consequences (Hokstad *et al.*, 2010; Shafiee; Animah; Simms, 2016) or greater risks (depending on the occurrence probability and consequence) (Hokstad *et al.*, 2010) for property, environment, downtimes, people and the company's image.

Supporting this, Hokstad *et al.* (2010) highlight that one of the main tasks during the decision-making process regarding LE consists in selecting and prioritizing the SCE that demand special attention.

Hence, the main objective of screening and prioritization of SCE is to focus limited resources on those SSC whose functions are more critical to safety, so that the prioritization of SCEs can substantially improve the reliability and productivity of equipment and processes and reduce associated risks (Shafiee; Animah; Simms, 2016).

Having this object as a guide, the operator should clearly define safety critical elements, that is, which SSC should be considered critical, as well as the effects that these elements are subjected to and the methodologies to identify them, according to the following subsections.

The operational SCE are characterized as (i) being related to the major accident hazards (MAHs) management, (ii) being specific for a particular facility and (iii) in general, having performance standards previously established.

Resolution ANP nº 43/2007 classifies the safety critical elements into three categories (ANP, 2007):

(1) Operational Safety Critical Equipment – Any equipment or structural element of the facility that could, in case of failure, cause or significantly contribute to a near miss or to an operational accident.

(2) Operational Safety Critical System – Any engineering control system built to maintain a facility within the operational safety limits, fully or partially stop the facility or a process, in case of operational safety failure or reduce human exposure to occasional failure consequences.

(3) Operational Safety Critical Procedure – A procedure or criteria used to control operational risks.

Sharp, Terry and Wintle (2011) list safety elements usually found in offshore production facilities, its main failure modes related to physical degradation and expected potential consequences during the ageing process of a facility (Table 1.3).

Table 1.3 - Typical failure modes causing physical degradation

SCE	Main failure modes related to physical degradation	Potential consequences of ageing
Hydrocarbon containment	Corrosion under insulation; Fatigue: vibration fatigue; Stress corrosion cracking; Process plant blocked by scale	Hydrocarbon releases; Potential for ignition, explosion and fire
Gas, smoke and fire alarms	Degradation of window material; Electrical faults; Poisoning of catalytic sensors; Corrosion of detectors or cable trays	Reduced efficiency in detection and loss of reaction time; Potential for larger releases and escalation
Emergency shut down (ESD) and blow down systems	Wear; Fouling; Corrosion and leakage; Obsolescence (non-availability of spares)	Hydrocarbon leakages and releases; Inability to close ESD and isolate system; Escalation of incident
Passive fire protection and fire walls	Wear; Exposure to ultraviolet light; Corrosion of material underneath coating; Ingress of water	Potential loss of structural capacity in jet fire; Escalation as fire degrades other SCE
Active fire protection	Water ingress into fire pumps	Fire pumps failure to start; Loss

SCE	Main failure modes related to physical degradation	Potential consequences of ageing
	controls/fuel; Corrosion of water pipes; Blocked pipes and sprays; Wear of pumps and valves	of capacity/efficiency in fire fighting protection; Escalation of fire
Temporary refuge (TR) Heating, Ventilating and Air Conditioning (HVAC)	Fouling; Wear; Corroded ducts and joints; Deterioration of damper performance	Slowing damper actuators; Reduction in fan speed; Toxic gas ingress; Asphyxiation
TR integrity/ Access routes to TR and evacuation stations	Wear; Deterioration of seals; General corrosion; Access obstructed	Failure of the TR to meet performance criteria; Casualties; Loss of time for evacuation

Source: Based on Sharp; Terry; Wintle, 2011

Additionally, the mentioned authors claim that the approaches usually established for the SCE management may not be enough when facility ageing becomes significant. As a consequence of the ageing process, the capability to meet the performance standards regarding functionality, availability, reliability and survivability tend to decrease, as detailed in Table 1.4. The cumulative ageing effects may result in systematic failures of multiple safety barriers (revealed and not revealed).

Table 1.4 - Performance standards

PERFORMANCE STANDARDS	AGEING EFFECT
FUNCTIONALITY	It can be reduced, progressively or predictably (e.g., pumping capacity, valve closure time), but also spontaneously or fast with few warnings (e.g., electric control systems)
AVAILABILITY	Tends to decrease due to the need of longer maintenance time. As the equipment becomes older, obtaining spare parts can become difficult and, at the same time, the maintenance teams may have greater difficulties in conducting the maintenance because of loss of familiarity with the equipment
RELIABILITY	Tends to decrease, as the SCE becomes more susceptible to failures when required or failures occur during operation.
SURVIVABILITY	Some systems can suffer long term deterioration, becoming less resistant to fire, explosion and overwork effects. Given this, the survivability of the SCE can be compromised.

Source: Based on Sharp; Terry; Wintle (2011)

Regarding interdependence (component failure that may weaken or cause failures in others), it is understood that the ageing process does not change or add new functional dependences among the systems and their components. Therefore, the functional dependences relations, dealt with in the literature as common causes of failure among the components, should be assessed during the whole operation period of the asset, not only for the LE period. This way, as an ageing effect, only an increase in the probability of these common causes occurrence can be cited.

Therefore, based on Table 1.4, it can be concluded that ageing requires a proactive management, and that the SCE may need revalidation, major repairs, renovation and replacement of key items (Sharp; Terry; Wintle, 2011).

The efforts used to develop reliability models for the SSC can be significant and can surpass/outgrow the benefits. Furthermore, according to Nitoi *et al.* (2011), these models are not always needed, which means it can do without the RUL estimative. This happens, mainly, in cases in which the methods that consider the operational record of maintenance, test, inspection and surveillance are enough to evaluate the ageing effects.

Different techniques have been used to select and to prioritize SCE, namely, Cause-Consequence Analysis (CCA), checklist analysis, Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Hazard and Operability Studies (HAZOP), Failure Mode and Effects Analysis (FMEA), Failure Mode, Effects and Criticality Analysis (FMECA) and What-if Analysis.

Nitoi and Rodionov (2010) introduce the use of the modified FMEA, named Advanced Failure Mode and Effects Analysis (AFMEA) to classify and to prioritize the SCE. AFMEA consists of a technique that has been applied in the nuclear energy industry to investigate the ageing effects in the critical systems vulnerabilities and has been considered a structured, sequential, and repeatable technique that, according to Shafiee, Animah and Simms (2016), can be executed by taking the following steps:

(1) Break the system down into subsystems;

(2) Identify the functions of the subsystems;

(3) Understand the stress and strain intensity factors for each subsystem and establish the possible ageing failure modes;

(4) Specify detection methods to each possible ageing failure mode;

(5) Evaluate the risk of each ageing failure mode, assigning indexes to severity (S), occurrence probability (O) and detection probability (D);

(6) Calculate the risk priority number (RPN) parameter, by multiplying severity classification, occurrence and detectability;

(7) Classify and prioritize the subsystems, according to their RPN values.

The RPN value varies between 1 and 1000, considering a range from 0 to 10 for S, O and D, and represents the effect or contribution of each ageing failure mode to the total risk for the system. The SSC based on its RPN values, are classified into three groups:

(1) less sensitive to ageing (less than 100 RPN)

(2) moderately sensitive to ageing (RPN between 100 and 200)

(3) highly sensitive to ageing (RPN greater than 200, components with high degradation rate).

1.3.4.4 Assessment of current condition

From the identification of the safety critical elements, the technical evaluation stage is started, which involves the application of condition assessment tools to determine current physical and functional health status of an asset (Shafiee; Animah; Simms, 2016).

Probabilistic Safety Assessment models, as analytical unavailability and lack of reliability models, were implemented in the nuclear industry to determine the current condition of the systems related to safety. The PHM has gained prominence regarding condition assessment and prediction of the RUL of systems related to safety. Methodologies of risk assessment, on the other hand, have been widely used for this purpose in some industries (Animah; Shafiee, 2018).

Regarding the latter methodology, a qualitative condition classification matrix is used to classify the risk related to the operation of the SCE, not only regarding probability but also the failures consequences are categorized in a scale. The color encoding consists in an acceptance criterion for risk related to the operation of SCE for some industries, such as electric power, oil and gas and petrochemical industry (Hameed; Khan, 2014 Amir; Muttalib, 2014; Carvalho *et al.*, 2015) according to Table 1.5.

Table 1.5 - Condition classification matrix

Probability of occurrence category						
Frequent	**5**	(2) Uncertain	(3) Poor	(3) Poor	(3) Poor	(3) Poor
Probable	**4**	(1) Good	(2) Uncertain	(2) Uncertain	(3) Poor	(3) Poor
Occasional	**3**	(1) Good	(2) Uncertain	(2) Uncertain	(2) Uncertain	(3) Poor
Remote	**2**	(1) Good	(1) Good	(2) Uncertain	(2) Uncertain	(2) Uncertain
Extremely unlikely	**1**	(1) Good	(1) Good	(1) Good	(1) Good	(1) Good
Consequence category		**1**	**2**	**3**	**4**	**5**
Operation condition		Minor maintenance activity	Minor maintenance activity	Minor maintenance activity	Longer shutdown with more significant cost of repair with implications on system availability	Permanent shutdown
Production loss		<5%	5–10%	10–30%	30–60%	>60%
Material degradation		No	Slight	Obvious	Serious	Extreme
Fatigue cracks (α)		No flaw	$0 < \alpha \leq 0.001$	$0.001 < \alpha \leq 0.03$	$0.03 < \alpha \leq 0.15$	$\alpha > 0.15$
Corrosion (η)		$\eta \leq 0.005$	$0.005 < \eta \leq 0.03$	$0.03 < \eta \leq 0.08$	$0.08 < \eta \leq 0.25$	$\eta > 0.25$

Source: Animah; Shafiee, 2018

Based on Table 1.5, three classifications can be defined for the condition of the asset (poor, uncertain and good), as proposed in Table 1.6.

Similarly, Shafiee, Animah and Simms (2016) propose a classification approach based on the assessment of the assets condition. The stages of this approach are described in Table 1.7.

Table 1.6 - Asset condition categorization

Class	Description
Poor	The condition of the subsystem or component is significantly outside design limits and should be discarded.
Uncertain	The condition of the subsystem or component may be outside design limit or unknown and RUL must be determined.
Good	The condition of the subsystem or component is within design limit and RUL do not have to be determined.

Source: Animah; Shafiee, 2018

Table 1.7 - Assessment classification approach

Steps	Formulation/Parameters			
Divide the condition assessment factors into history and health factors, assign a score (between 1 and 4) to each condition assessment factor, based on the data available and the knowledge and experience of field experts or assessment team.	Rating	Score	Risk Level	Condition
	A	4	None	Normal
	B	3	Low	Moderately normal
	C	2	Moderate	Not normal
	D	1	High	Worst
Determine the Condition Index (CI) - Sum up the weighted scores for history and health factors to obtain the asset condition score.	CI = $\sum_{i=1}^{n}(S_i)(w_i)$; where $\sum_{i=1}^{n}(w_i)$ n - number of elements (parameters) considered in each factor; S_i - rating score of the i^{th} element; w_i - relative importance (weight) of element I; CI = $\alpha \times$ history score + $(1 - \alpha) \times$ health score, $0 < \alpha < 1$ α, $(1-\alpha)$ – relative importance of history and heath factors in relation to each other.			
Display the sub-system health condition in three colors of green, yellow and red according to the value of condition indexes.	CI		Asset health condition	
	[4.0–3.5]		Green	
	[3.5–3.0]		Yellow	
	[3.0–0.0]		Red	

Source: Based on Shafiee; Animah; Simms, 2016

The stages described are repeated to every subsystem of the SCE.

The subsystems whose integrity conditions are shown in green their RUL will not need to be estimated and must proceed to the obsolescence and organizational issues assessment, proceeding to item 1.3.6.

The red zone represents intolerable risk and those subsystems that fall into this category are not technically qualified for LE. The red zone represents that it was not possible to identify measures or the selected measures were considered not applicable or not accepted within the analysis context; in this case, the LE process of the SCE will be rejected and the decommissioning will be the only option to the end of the SCE life cycle. The yellow zone is a warning zone; some further safety and/or process control measures must thus be added before the subsystem can be considered for LE (Shafiee; Animah; Simms, 2016; Animah, Shafiee, 2018) in order to reduce the associated risk.

1.3.5 Assessment of remaining useful life (RUL)

RUL refers to a function whose estimated failure time of the SSC is defined, that is, conclusion on the ability to perform a necessary function, considering the current operational, historical and future conditions (Banjevic, Jardine, 2006; Vaidya; Rausand, 2011; Galar *et al.*, 2012). Liao, Zhao and Guo (2006) clarify that the preliminary RUL estimated during the project phase is usually conservative, as, in practice, the real environmental and operational conditions might be different from the ones considered during the project phase.

The RUL calculation supports the decision-making process for the LE strategy and consists in one of the main factors that should be considered in the implementation of condition monitoring (CM) and PHM (Cui; Loh; Xie, 2004; Lee *et al.*, 2006). The literature shows several methods to estimate RUL (Jardine; Lin; Banjevic, 2006; Galar *et al.*, 2012), not only deterministic but also probabilistic (Animah; Shafiee, 2018).

In general, the RUL estimation methods are classified as follows: approach based on physical condition, data-oriented approach and hybrid approach (Banjevic; Jardine, 2006; Shafiee; Animah, 2017), according to Table 1.8.

Table 1.8 - Approaches to estimate RUL

Types of Approach	Fundamental Principle	Characteristics
Based on physical condition	Formulation of theoretical mathematical models to understand equipment degradation and damage modelling over time.	Failure modes assessment, with crack spreading, wear and corrosion degradation rate of the equipment.
Data-oriented	Sensors network to monitor the health status of the equipment	The data are collected from sensor signals and prediction models, such as Bayesian models, Cox models, regression models, etc., are used to estimate the RUL of the equipment.
Fusion/ Hybrid	Overcome the limitations of the physical condition based and data-oriented approaches	Combines data acquired from sensors, as well as monitoring data based on physical condition to create a new database.

Source: Based on Cheng; Pecht, 2009; Galar *et al.*, 2012; Varde; Tian; Pecht, 2014; Animah; Shafiee, 2018

Vaidya (2010) and Vaidya and Rausand (2011) classify the factors that influence the RUL estimative into three types: physical integrity of the asset, project phase information and environmental condition, according to Table 1.9.

Table 1.9 - Factors that affect the RUL estimative

Factors	Details
Asset physical condition	Cumulative knowledge about an asset at that specific moment. The technical health status of the equipment is interpreted based on its technical conditions and life cycle records.
Information from the project phase	Information regarding material selection, equipment specification, codes and project standards, project designs, life cycle calculations and post-project engineering variations.
Environmental conditions	Predicted during the early stages of the life cycle of the asset, can change over time, for the asset can be subjected to different environmental conditions. It can not only introduce new failure modes, but also increase the deterioration rate of the existing growing faults. Therefore, it is essential that the technical health assessment of an asset

Factors	Details
	considers the environmental conditions in which the asset is operating.

Source: Based on Vaidya, 2010; Vaidya; Rausand, 2011

To calculate RUL, Animah and Shafiee (2018) suggest the following stages: data gathering, assessment of failure mechanism and selection of the prediction RUL model, according to Table 1.10. After undergoing these stages, the calculated RUL is compared with the proposed life cycle.

Table 1.10 - Stages for RUL estimative

Stage	Details
Data gathering	Project information – structure designs, loading details, structural calculations, finite element models available, fabrication and installation reports and accidents during the survey, transport and installation phases. Operational phase information – Accidents and incidents during life cycle, structural damage and changes, risk analysis reports, inspection and maintenance reports, material tests reports, repairs executed during operation.
Assessment of failure mechanisms	Assessment of the several failure mechanisms related to the failure modes. Definition and detailing regarding the main failure mechanisms that affect the functionality of a subsystem or component.
Selection of the RUL prediction model	LE estimation models in the offshore oil and gas industry to predict the RUL of a system and structures include Bayesian models, stochastic and statistical models, computational intelligence models, physical failure models and specialist judgement, among others.

Source: Based on Vaidya; Rausand, 2011; Animah; Shafiee, 2018

In case the RUL calculation results in a smaller value than the proposed extended life period, additional mitigation measures can be defined. The following mitigating measures can be taken: (i) changes in the inspection, test and maintenance program (Franklin *et al.*, 2008; Hokstad *et al.*, 2010), such as, for example, identifying the need to increase inspection frequency or proposing distinguished inspection; (ii) changes in the SSC operational condition during extended life cycle; (iii) strenghtening of some operational conditions, such as identifying the need to install condition monitoring methods or supporting overloaded areas.

From the set of additional risk reducing and mitigating measures, the matching RUL should be calculated. In case the RUL calculation results in a value that is equal or greater than the one proposed, one must proceed to the obsolescence and organizational issues assessment, proceeding to item 1.3.6. If not, a new LE period must be defined, returning to item 1.3.2.

1.3.6 Evaluation of obsolescence and organizational issues

According to section 1.3 herein, obsolescence assessment involves matters associated with outdated equipment, new technologies, new requirements and regulations and new needs. Complementarily, the evaluation of the organizational issues comprises personnel ageing, knowledge transfer and reorganization of the company.

According to the framework in Figure 1.4, the obsolescence and organizational issues assessments should consider the evaluation of the current condition of the asset and, together with this analysis, be an input to the definition of the LE strategy.

In this article, the obsolescence and organizational issues assessments had a preliminary approach and will be broadened and deepened in further studies. Also, some proposed thoughts should be observed by the operator to define the LE strategy that should be adopted (Hokstad *et al.*, 2010). These thoughts are structured in the form of questions, according to Table 1.11 and Table 1.12.

Table 1.11 - Questions regarding obsolescence thoughts

Types	Questions
Outdated equipment	- What is the current equipment reliability? Is this reliability reducing over time? - Is the equipment easy to maintain? Are the spare pieces and parts promptly available or are of easy reverse engineering? - When repairs are made, is there the possibility to introduce more damage to the equipment (such as damage increase due to difficulties in welding or due to restrict access to welding)? - Considering that as a facility ages, there is a tendency to replace equipment with temporary ones, is the personnel competence enough to deal with temporary equipment? - Are there any companies capable of providing spare parts or services when demanded? - Is it possible to have a lack of spare parts or technical support for the equipment in the future? - Are the abilities needed to manage the old equipment (maintenance, inspection, operation, among others) rare or did it become obsolete? Is there formal training in theses "obsolete" skills available? - Does the supplier have the necessary skills to offer support to old equipment? In case important spare parts are not available, are other maintenance plans identified? - Were there measures to guarantee that spare parts or consumables that may be vulnerable to degradation due to stocking environment (such as temperature, humidity, chemical product, dust) are stocked in an adequate controlled environment? - Was there planning for supplying spare parts for the whole LE period, reallocating parts, long term agreements with suppliers and developing structures or equivalent components? - Is the availability of spare parts being continuously monitored and controlled?
New technologies	- What is the impact of the new technology regarding safety when compared

Types	Questions
	with the previous technology? - Is there enough knowledge regarding the new technology and its use? - Are the facility and the close equipment compatible with the new technology? Will there be enough knowledge about the new technology? - Considering the current condition of the old equipment, what might be the consequences of having old and new equipment in the facility?
New requirements and/or regulations	- What are the standards, regulations and requirements relevant for the SSC (including the operation of the equipment)? - Is there enough knowledge about the current requirements and regulations? Which original standards/regulations are still applicable? - What are the gaps between the current standards, regulations and requirements and those used to design the equipment? - Do the regulators require standards which are hard to comply with?
New needs	- Was there a comparative assessment of the old and latest projects regarding complexity? - Was there an evaluation to verify if the equipment was originally designed to comply with other parameters (such as liquid type, other temperatures and pressure conditions), which would result in greater risk and lesser reliability on the new operation? - Was there an evaluation of the layout and increase in load due to new types of operation, modifications and new technologies? - Might there be a lack of space, hindering access to the facility or greater complexity?

Source: The author, 2024

Table 1.12 - Questions regarding organizational issues

Types	Questions
Personnel ageing	- Are there challenges regarding personnel ageing (e.g. due to retirement or management changes)? - Knowledge maintenance: Is there experience, competence and knowledge enough to keep the facility at a satisfactory safety level? - What is the knowledge quality regarding future operation, using the available equipment and the combination of new and old equipment in specific facilities? - What about temporary equipment? - Do the personnel understand the relevant degradation processes and the risk reduction/compensation measures to prevent or reduce degradation? - In case maintenance is carried out by groups that work in different facilities and not by workers of a specific facility, is the maintenance group competent to deal with the specific facility and its equipment and operation?
Knowledge transfer	- Is the competence of LE assessment available in the company? - Does the operator guarantee that the LE experience acquired in other facilities and operational areas are applied to the analyses and evaluations? - Does the operator know the best practices applied to LE, within or outside the company? - Are the complex ageing questions dealt with an interdisciplinary approach with the members of operation, maintenance, engineering, project and research and development? - What are critical competences to be kept in the company? - How is the knowledge of personnel that retire or leave the company kept? - Is there enough competence/knowledge transfer from the personnel that retire or leave the company? - Which competence might “disappear”? - Are there mechanisms to transfer knowledge in the company?
Reorganization	- Was there reorganization of the company that might impact the facility?

Source: The author, 2024

When the challenges related to obsolescence and organizational issues are mapped, one should search for the possible deviations, the current condition and the required condition of the facility, considering the current requirements and future operational needs of the asset, besides the foreseen performance of the facility during the extended life period.

From the gaps identified, possible additional measures to be implemented by the operator are assessed to solve the insufficiencies/deviations or minimize the risks associated with these deviations are evaluated. A gap analysis must be performed so that it guarantees that the combined effects do not compromise the fulfillment of the specified risk acceptance criteria.

1.3.7 Definition of LE strategy

Based on the asset condition assessment and the obsolescence and organizational issues assessment, the strategy for the LE period must be defined.

The LE decisions include the ones shown in Table 1.13.

Table 1.13 - LE strategies

Strategies	Description	Condition	Advantages and disadvantages
Replacement (repowering)	Replacement of an existing system or component with a new one or upgrade of the system to higher nameplate capacity at the end of its original life irrespective of functional status.	Returns the system to “as good as new (AGAN)” condition.	Can be very cost-intensive, may cause safety risks and lead to long downtime periods.
Reconditioning	Involves taking appropriate actions at specific time periods to ensure that the system continues to perform its required functions.	It restores a system between AGAN and “as bad as old (ABAO)” condition.	Few parts are required to be replaced thereby reducing material costs. However, labor cost will be high since many parts may need to be repaired.
Remanufacturing	Integrates processes or techniques such as reconditioning, replacement and repair of some parts.	Return an existing system to at least original equipment manufacturer (OEM) functional specifications with warranty.	Reduces usage of materials, reducing workload and retaining profit by lowering production cost. Requires high investment in hardware and software. Not applicable to the SCEs which cannot be dismantled or disassembled.
Retrofitting	Replacement of old components or equipment in an installation with modern equivalent. It is conducive for equipment or components		Improved functionality, availability, safety and also reduced equipment downtime.

Strategies	Description	Condition	Advantages and disadvantages
	having high maintenance cost and/or failure rate.		
Re-use	It is the process of operating equipment or components in an installation until the end of their economic life.		Improvement of reliability, availability, and serviceability (RAS) of equipment in the long-term.
Refurbishment	Actions performed near the end of life to return a system to its functional state. This strategy integrates partial replacement, reconditioning and partial redesigning.	Achieve a performance higher than OEM functional requirement.	High labour cost and addition of extra materials while ensuring high level of reliability during the LE phase of operation.
Reclaiming	It is a process of refining lubricant oils by eliminating all contaminants and insoluble particles to attain oil with characteristics similar to those of a new one.		Reduced system outage, hence less downtime, re-use of old oil, no disassembling and reduced material usage. High possibility of injury caused by sulphuric acid.
Retrofilling	It is a process of replacing existing lubricant oils with natural ester dielectric coolant.		Presents similar advantages to reclaiming; however, unlike reclaiming, the old oil is disposed-off.
Repair	Restores a system to functional condition either when it fails or on a planned schedule. This strategy is adopted for LE of complex engineering systems seeing that different subsystems and components may have different life expectancy.		Less expensive as compared to the replacement/ repowering strategy.

Source: Shafiee; Animah; Simms, 2016; Shafiee; Animah, 2017; Franklin *et al.*, 2008

1.3.8 Assessment of economic issues

Although technical qualification is a key to guarantee safe operation and reliability of the SCE during the LE period, the economic assessment of the project must not be ignored.

To assess the economic feasibility of the LE plans, an economic index (EI) based on the assessment of the benefits and costs is shown (Shafiee; Animah; Simms, 2016), according to Table 1.14.

Table 1.14 - LE benefits and costs

Benefits (B)	B1 – Increased production	B1a - Reduced equipment downtime
		B1b – Increased revenue
	B2 – Improved safety	B2a – Reduced injury to personnel
		B2b – Reduced death rate
		B2b – Reduced equipment failure rate
	B3 – Delayed decommission cost	
Costs (C)	C1 – Capital cost	C1a - Cost of purchasing new equipment
		C1b - Cost of hardware upgrading
		C1c - Cost of software upgrading
	C2 – Installation cost	C2a - Labor cost
		C2b - Downtime cost
		C2c – Logistical support cost
	C3 – Operating expenditure	C3a - Maintenance cost
		C3b - Royalty cost
		C3c - Logistical support cost
		C3d - Taxes

Source: Based on Shafiee; Animah; Simms, 2016

Finally, the EI can be determined by using Net Present Value (NPV) or Benefit-Cost-Ratio (BCR). If the NPV for a LE solution becomes non-negative (i.e., NPV ≥ 0), then the EI is assigned to be one; otherwise, if NPV < 0, the index is assigned a zero value (Shafiee; Animah; Simms, 2016).

1.3.9 Definition of a LE management plan

The LE process must be documented before its implementation. The elaboration of a LE Management Plan is essential for systematizing the management of the ageing process, once the documentation reveals all the actions and monitoring details the operator must perform to guarantee the implementation of the LE strategy established.

The detailed documentation that justifies the LE must be prepared and submitted for approval from the third-party authorities, depending on the country's regulation (Franklin *et al.*, 2008).

This Plan must include:

(1) Results summarizing the technical assessment of the asset.

(2) Overview, as well as premises and limitations of the decisions taken during the process of defining the LE strategy.

(3) Statement of the adopted strategy for each SSC analyzed

(4) Adequate inspection, test and maintenance program to ensure integrity during the SSC life cycle (Norsok, 2017, 2009; American Petroleum Institute, 2014; Lotsberg *et al.*, 2016).

The objective of this program is to control the risks related to SSC degradation (Liu *et al.*, 2015). The intervals to condition monitoring must be adjusted to consider the highest failure probability due to damage backlogging in the beginning of the project (NORSOK, 2017). Additionally, the most suitable inspection, test and maintenance method must be selected, considering the characteristics of each SSC and its respective failure modes.

(5) Specification of use of indicators during the LE period

Using indicators to evaluate safety integrity is important for follow-up and decision-making during the operation of ageing facilities (Hokstad *et al.*, 2010; Liu *et al.*, 2015).

Tracking integrity indicators can provide decision-makers with signs or evidence that some damage has already occurred or is about to occur and can be thought of as symptoms of ageing damage. There are various types of indicators: (i) inspection/monitoring results; (ii) the occurrence of specific failures/failure modes (failure analysis); (iii) number of various undesired events; (iv) performance of process, among others (Hokstad *et al.*, 2010).

The use of indicators must not be limited to monitoring the assessment of material physical degradation, but include other ageing approaches (obsolescence and organizational issues), as well as the financial aspect of the LE process.

Sharp, Terry and Wintle (2011) define two types of performance indicators (PI) to evaluate the management of the ageing effects on SCE and how effectively the ageing management processes are being conducted:

- SCE hardware PIs - comprise detailed measurement results from tests and inspection activities and represent lagging indicators;

The indicators must be able to continuously monitor the operational parameters to verify the behavior trend and enable the comparison with future conditions used as premises in the stage of assessing the condition of the asset.

- Process PIs - represent measures of the processes for managing the effects of ageing on SCE as a whole. They are usually developed from aggregated data and can be used as leading indicators.

The indicators must be able to continuously monitor whether the actions defined and listed in the LE Management Plan are being adopted and have been effective in managing the effects of ageing.

These indicators take into account, for example: (i) numbers and types of incidents, (ii) numbers and types of unplanned downtime and production losses, (iii) total maintenance delays, (iv) unavailability or lack of performance from main safety systems, (v) feedback from regulatory compliance inspections, among other information.

(6) Plan to ensure that the necessary spare parts are available throughout the extended life.

(7) Identification of specific procedures to be implemented during LE (Hokstad *et al.*, 2010), such as: distinguished inspections, monitoring operational parameters, registers and data gathering, among others;

(8) List of mitigation measures ranked to reduce risk during the technical assessment.

1.3.10 Obtaining regulatory approval

An LE plan must be supported by engineering and technical documentation for justifying the continuous operation of SCEs beyond their original design life.

The main purpose of regulatory consideration and approval is to thoroughly assess the documentation submitted by operators and to ensure that SCEs can perform their intended functions during the extended life of operation in accordance with the relevant regulations.

Regulators are required to review and to verify that the LE plan is consistent with current regulations and industry-approved standards. In case a SCE is not qualified for LE at the approval stage, a recommendation is made as to whether decommission the facilities (Shafiee; Animah; Simms, 2016).

1.3.11 Implementation of LE management plan

After following the previous stages, if the assessment of the overall risk picture is acceptable, considering the aspects of ageing and the risk reducing measures, the LE Management Plan should be implemented. The plan should ensure the technical, operational and organizational integrity of the facility during a LE period (HOKSTAD *et al.*, 2010).

1.3.12 Monitoring the life extension management plan effectiveness

Sharp, Terry and Wintle (2011) establish a monitoring procedure for the LE Management Plan effectiveness from a capability maturing model (CMM) developed. In this approach, five capability maturing levels were described for the process, allowing assigning a maturity level to the organization according to how the ageing effects are being managed. The five levels of maturity are described in Table 1.15.

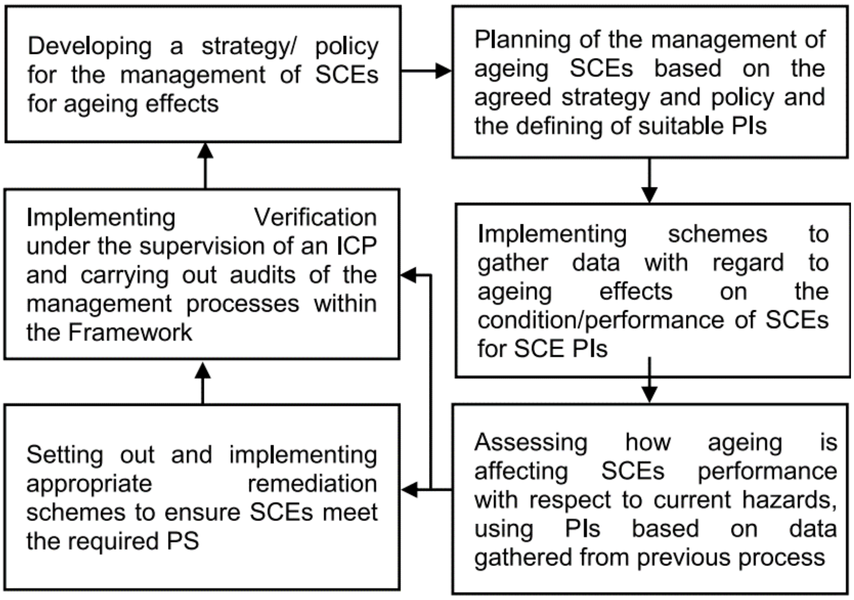
Table 1.15 - Maturity levels description

	Maturity Level	Description
1	Basic (Learner)	The processes are either absent or ad-hoc without any real understanding of what is required to manage the ageing of SCEs.
2	Localised (Repeatable)	The processes are organized and controlled at the local working level, without any proper procedures in place. Problems in managing the ageing of SCEs are not usually reported unless they significantly affect safety production or cost.
3	Defined (Standardized)	Written procedures which define the management of ageing in SCEs to achieve their required PSs are available and implemented across the organization. There is an understanding of the basic requirements to manage the ageing of SCEs, but little use is made of any data collected to effect change and improvement.
4	Managed	The organization has an understanding of how to set targets for the management of the ageing of SCEs from experience, research and development and how to include the supply chain in achieving good performance. Processes are adapted and performance improved in response to observed failures in the management of the ageing of SCEs.
5	Optimised	The organization has developed a good understanding of how to continuously improve the management of the ageing of SCEs, based on up-to-date knowledge, worldwide experience and appropriate research and development processes, procedures and targets are regularly monitored, researched and discussed. Communications and learning are optimised across the organization to develop and disseminate best practice. Training and appropriate competence are optimised, including the development of training methods and materials across the organization and the supply chain.

Source: Shafiee; Animah; Simms, 2016

Besides the maturity level of the organization, from the six processes framework (Figure 1.6), it is possible to evaluate the efficiency level attained by an organization managing its SCE during its LE period. The six processes are expected to be completed at different levels within the organization.

Figure 1.6 - Processes for ageing management



Source: Sharp; Terry; Wintle, 2011

Whenever the indicators are in accordance with the established goals, LE should be continued, maintaining monitoring throughout the extended life period, until decommissioning.

If any performance indicator is not in accordance with the goals, the situation should be assessed. If the identified deviation has a technical nature, a new assessment of the current condition of the asset must be carried out, returning to item 1.3.4.4. If it is of an economic nature, a new economic assessment must be carried out, returning to item 1.3.8. In both cases, regardless of its nature, the objective should be to identify possible ways to get around the problem.

1.4 Case Study

This section will present three real case studies related to LE in offshore production facilities submitted to the Agency's evaluation and a hypothetical case of a subsea interconnection system that is part of the outflow system of an offshore production field.

The presentation and analysis of real cases aims to comparatively evaluate the information contained in the LE processes of offshore production units and those identified as necessary for the development of the steps proposed in the framework presented in this article. From this comparison, it is possible to identify evident gaps between the level of completeness of the information actually provided in the cases already submitted to the Brazilian regulatory agency and that considered necessary for a well-based decision.

In this sense, upon the realization that the identified real cases do not allow an evaluation of the contribution and adequacy of the proposed framework in its entirety, the proposed framework was also applied to a hypothetical case.

The hypothetical case was developed based on facts reported by a major operator in Brazil and aimed to analyze and highlight the contribution of each stage of the proposed guideline. To this end, all the steps proposed in the framework for evaluating the LE process were followed, taking as an example one of the approaches and methodologies presented in the respective sections of 1.3.1 to 1.3.12.

1.4.1 Real cases

There are currently three processes submitted to the Agency in which the operators sign the need/opportunity to extend the life cycle of a field as a whole. These three processes belong to different operators, comprising national and international operators, including assets located in different basins and production fields.

Note that these three case studies (case 1, case 2 and case 3) are at different detail levels regarding the LE process, which can be justified by the following issues:

(i) Maturity level of the operator. There are operators that already possess experience in assessing certain aspects of the LE process, particularly those related to the assessment of material degradation. This occurs because, during the field operation, they had to outline challenges regarding mechanical integrity due to the reduction of the life cycle of components and, therefore, they acquired experience on this topic. In such cases, the studies show deeper aspects related to the physical degradation of the material. Case 1 fits this condition and was presented by the operator with the highest level of maturity when it comes to useful LE.

(ii) Proximity to the end of the field life cycle. In general, the ones that already extended the life cycle of the asset or are very close to the end of the designed life cycle of their SSC usually have already conducted an LE assessment. In this case, therefore, the detailing level of the studies presented is higher. A greater proximity of the field's end of life is observed in cases 1 and 2.

(iii) No intention of staying on the field after LE. In general, the operator that intends to give away the right to explore a field to another company submits the LE studies with a lower detailing level, understanding that further studies can be performed by the other company. The intention to sell the asset is seen in case 3.

Based on the available information submitted to the Agency, Table 1.16 was created, aiming to identify whether the main objective of each stage proposed by the framework was met by the corresponding operators. It should be highlighted that the 'check' symbol means that the operator approached the subject, which does not mean that the methodologies shown in the stages described in this article were used, or that the stages were fully addressed, going through every corresponding activity.

Table 1.16 - Documentation comparison with the stages of the proposed guideline

Item	Stages of the Ageing Process Management	Process		
		1	2	3
1.3.1	Definition of LE motivation	✓	✓	✓
1.3.2	Definition of LE period	✓	✓	-
1.3.3	Definition of LE premises	✓	✓	-
1.3.4	Evaluation of asset condition	✓	✓	-
1.3.4.1	Evaluation of available information	✓	✓	-
1.3.4.2	Breakdown of systems into manageable units	✓	✓	-
1.3.4.3	Screening and prioritization of SSC	✓	-	-
1.3.4.4	Assessment of current condition	✓	✓	-
1.3.5	Assessment of Remaining Useful Life (RUL)	✓	✓	-
1.3.6	Evaluation of obsolescence and organizational issues	-	-	-
1.3.7	Definition of LE strategy	-	-	-
1.3.8	Assessment of economic issues	-	-	-
1.3.9	Definition of a LE Management Plan	✓	-	-
1.3.10	Obtaining regulatory approval	✓	✓	-
1.3.11	Implementation of LE Management Plan	-	-	-
1.3.12	Monitoring the LE Management Plan effectiveness	-	-	-

Source: The author, 2024

Considering Table 1.16 for the processes numbered 1 and 2 and that process number 3 regards an operator that is still in a very initial stage of development of a LE plan for its assets (still has not defined the proposed LE period), the following can be highlighted:

(i) The operators focus their analyses on technical aspects, mainly material degradation.

Depending on the level of detail of the studies, the condition of the assets is evaluated, and the RUL calculated. However, this evaluation is not complete, as proposed in stages 1.3.4 and 1.3.5.

With respect to item 1.3.4, the assessment of the condition of the asset presented in cases 1 and 2 does not demonstrate to be the result of an established and structured analysis process. It was to be expected a process based on data and information available on the asset, on the segmentation of critical and non-critical SSCs and on a risk analysis, even if qualitative, to identify the critical SSCs for which the RUL values need to be estimated.

As submitted, the analysis of the asset's current condition gives rise to innumerable doubts for the regulatory agency, like lack of clarity regarding the scope of the analysis and the reasons why certain components were not objects of an evaluation and RUL calculation.

With respect to item 1.3.5, the prediction of RUL presented in cases 1 and 2, in particular for SSCs whose RUL estimate was not compatible with the LE intended by the operators, did not result in inputs that should be deployed in other stages of the analysis. The proposition of mitigating measures, for example, does not contribute to the definition of the strategy to be adopted for the asset nor did it lead to the implementation of monitoring measures, demonstrating once again the lack of structure between the stages of analysis.

(ii) The operators do not analyze the other technical aspects of LE: obsolescence and organizational issues.

The technical studies presented to the regulator in cases 1 and 2 reveal that, in fact, the operators do not analyze the ageing process of their facilities in a comprehensive manner. It is clear that the three aspects of ageing are not evaluated, and in particular those related to obsolescence and organizational aspects.

However, it should be noted that these two neglected aspects are very relevant for cases 1 and 2, considering that the intended operational extension occurs in assets with more than 25 years of operation, which have equipment with outdated technologies and that, in part, do not meet the updated legislations.

Additionally, these facilities have teams that have followed the asset's operational life for decades, which will invariably bring future questions involving staff competence, knowledge transfer and other issues regarding the organization's ability to deal with the challenges of the LE process.

It can be highlighted that, based on the framework proposed, the three approaches (material degradation, obsolescence and organizational issues) clearly influence the final decision of LE and are inputs to define the strategy to be adopted in this process.

(iii) The operators do not show the assessment from an economic point of view which in part support the LE strategy chosen, or the strategies they intend to adopt (case 1, 2 and 3).

The LE Management Plan presented in case 1 shows motivation and some premises used but does not specify, for example, the indicators that will be used to monitor the effectiveness of the plan and the other aspects listed throughout section 1.3.9 of the article.

Therefore, it is understood that the information submitted to the regulatory body in the processes related to the three case studies is too incipient and does not show robustness or the details needed to: identify the risks, mitigate the challenges associated with LE, fully identify the scenario analyzed by the operator, explain the strategy to be adopted, implementation plan, monitor the process during LE period or the criteria that would result in operation interruption or decommissioning of the asset.

The deficiencies pointed out can be attributed to two factors: (i) lack of operator experience regarding the LE process, considering that these are the first studies to be submitted to ANP, and (ii) no specific regulations or guidance documents for the LE process, created by the Regulatory Body or by independent institutions.

The two points above highlight the contribution of the proposed framework.

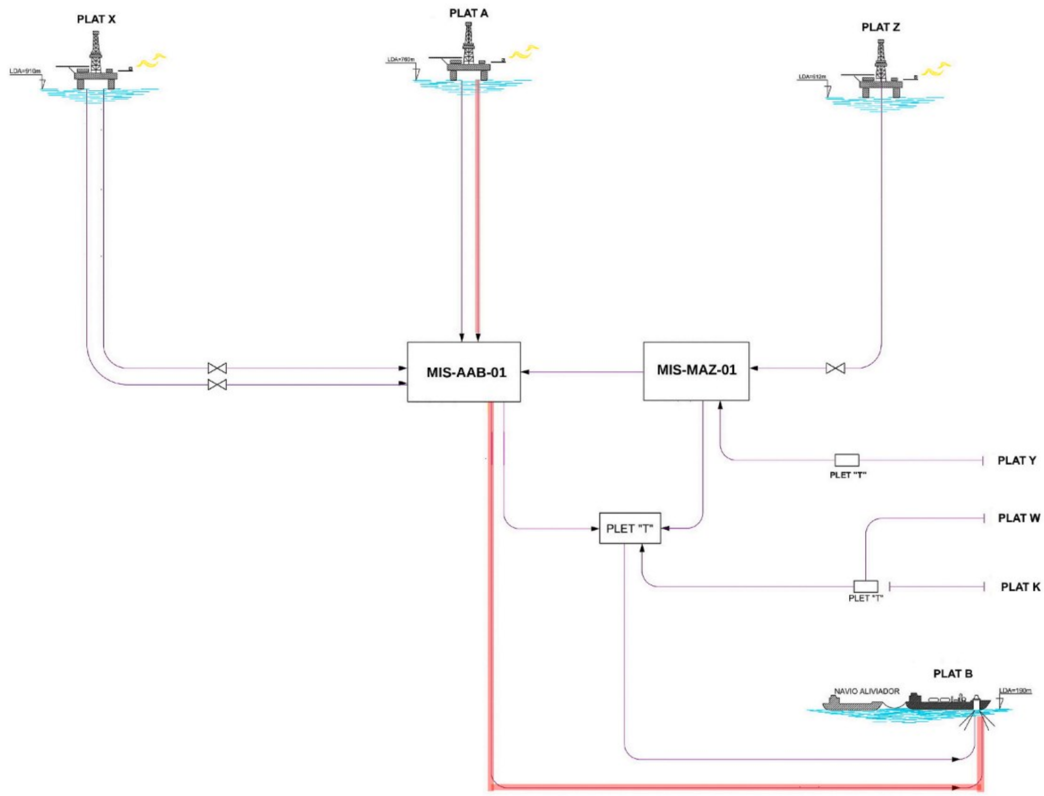
In this sense, the framework proposed in the article can be considered a first approach carried out taking into consideration all the steps for managing the LE process of oil and gas facilities, setting a direction for both operators and regulators.

1.4.2 Hypothetical cases

For the assessment of the potential contribution of the guideline proposed in this article, it will be applied in its entirety to the evaluation of the extension of the useful life of a hypothetical subsea interconnection system. In this case, such system will be used for the outflow of the production of an offshore unit (PLAT A) to a Floating Production Storage and Offloading unit (FPSO) (PLAT B), which in turn will treat the received production in its processing plant and export it through a relief ship.

Figure 1.7 shows a diagram of the facility under consideration where the subsea interconnection system to be evaluated is highlighted in red. Such system will be referenced to throughout this section as “subsea production system".

Figure 1.7 - Diagram of the production outflow system



Source: The author, 2024

Hypothetically, it will be considered that the cited subsea production system has some components that have reached their useful life as defined in the project. The evaluation of the system’s useful LE will follow the twelve stages detailed in the flowchart of Figure 1.4, according to the following sub-items.

The identification and description of the system components is the scope of a specific stage of the proposed guideline that will be described in section 1.4.2.4.2.

1.4.2.1 Definition of life extension motivation

The motivation for the extension of the useful life is that the subsea interconnection system between PLAT A and PLAT B, considering all its components, has a designed useful life shorter than that defined for the topside structure of offshore facilities.

Therefore, in order to maintain the oil and gas flow from PLAT A to PLAT B, the possibility of extending the operational life of the interconnection without the need to replace the whole system needs to be evaluated. This assessment is justified by the possibility that a complete replacement of the interconnection system could render the operational continuity of both platforms unfeasible from the economic and financial viewpoint.

1.4.2.2 Definition of life extension period

Considering that:

(i) the useful life considered in the design of offshore production facilities, which the subsea system interconnects, is 20 years, and at the moment both have a remaining useful life of 5 years, and

(ii) according to the project, the subsea interconnection system between PLAT A and PLAT B – considering all its components – has already reached its useful life expectation,

the intended extension of the system's life is 5 years.

1.4.2.3 Definition of life extension premises

The premises for the assessment of the subsea interconnection system between PLAT A and PLAT B consist of:

(i) promoting the alignment between the remaining useful lives of both the topside of the offshore production facilities and the subsea production system;

(ii) guarantee the operational continuity of the offshore production facilities;

(iii) guarantee the operational safety of the subsea production system, and

(iv) postpone the decommissioning of the subsea production system for the asset in question.

1.4.2.4 Evaluation of asset condition

1.4.2.4.1 Evaluation of available information.

The information available for the system under evaluation is quite detailed, consisting of:

(i) incident data and system design information, containing data sheets for each of its components and the layout of the subsea system;

(ii) a list of all the management of changes occurred during the operational life of the subsea production system;

(iii) reports of installation of the subsea production system, containing, for example, the main loads to which the components were subjected during the installation, and the respective acceptance by the operational team when the system was received;

(iv) "as built" of the subsea production system post-installation;

(v) data from the integrity management system, providing detailed information on tests and monitoring performed on each of the components of the subsea production system during its operational life (for example, visual inspections, cleaning PIG, instrumented PIG, measurement of structures potential);

(a) This information details the periodicity of the tests and monitoring performed along with their results, the resulting recommendations and corrective/preventive actions implemented (for example, the injection of chemicals into the pipelines).

(vi) data on the main mechanisms and failure modes recorded during the operational life of the system.

(vii) Incident data and detailed reports of the respective investigations, detailing the lessons learned.

In addition to the information and characteristics of the subsea production system mentioned above, there is a history of information concerning the period of operation of the system, encompassing the characteristics of the fluid coming from PLAT A (for example, corrosivity potential), the system's operational parameters (for example, pressure, temperature) and the characteristics of the reservoir and its parameters (for example, BSW, CO_2 and H_2S levels).

Regarding the information available for the intended period of time, it is understood that:

(i) in terms of regulation, the new requirements contained in ANP Resolution 41 (2015) (ANP, 2015) – which laid out the operational safety management for subsea systems – and were not observed at the time of installation/operation of the system must be taken into consideration; and

(ii) considering that the asset is in a mature field, significant changes in terms of reservoir characteristics and the like are not expected, allowing for keeping in place the same operational procedures as in the last 2 years of the system.

1.4.2.4.2 Breakdown of systems into manageable units

The subsea production system, identified in Figure 1.7, comprises the components shown in Table 1.17. To make the arrangement of the components shown in Table 1.17 easier to understand, Figure 1.8 depicts a simplification of the subsea production system whose possible LE is under analysis.

Table 1.17 - Components of the subsea production system

Item under evaluation	Type of component	Component identification	Length (meters)	Diameter (inches)	Date of first installation
1	PIG launcher	LP-123456	-	-	Aug/2005
2	Surface pipes	12-P-F-116	-	-	Aug/2005
3	Rigid spool (submerged)	12-P-F-116	-	-	Aug/2005
4	Flexible riser	TR1234567	700	11	May/2005
5	Flexible riser	TR1234568	650	11	May/2005
6	Rigid stretch	1234	9200	12	Jan/1999

Item under evaluation	Type of component	Component identification	Length (meters)	Diameter (inches)	Date of first installation
7	Rigid stretch	1235	8500	12	Feb/1999
8	TIE-IN	12345	36	12	Feb/1999
9	Manifold	MIS-AAA-01	-	-	Jan/2000
10	TIE-IN	12346	25	12	Feb/1999
11	Rigid stretch	1233	3300	12	Feb/1999
12	Rigid stretch	TR1234569	480	11	Feb/2000
13	Closing spool (emerged)	SF-S-01_plat A	-	-	Dec/2000
14	Surface pipes	12-P-F-115	-	-	Dec/2000
15	PIG receiver	RP-123456	-	-	Dec/2000

Source: The author, 2024

Figure 1.8 - Simplification of the subsea production system under analysis

Source: The author, 2024

1.4.2.4.3 Screening and prioritization of systems, subsystems and components (SSC).

Based on the methodology presented by Nitoi *et al.* (2011), as discussed and proposed in section 1.3.4.3, the functions and stress factors for each subsystem listed in Table 1.17 and the detection methods for each possible failure mode were identified, with emphasis being given to those associated with ageing. Based on this information, the risk of each failure mode associated with ageing was assessed, with indexes being assigned to S (severity), O (probability of occurrence) and D (probability of detection), resulting in the parameter RPN (risk priority number).

The methodologies used in the analysis of each failure mode take into account standards, norms, technical recommendations and recommended practices. These analyses consider the following aspects to define parameters S, O and D, when applicable and available, given the particularities of each component:

(i) the probability of failure considered;

(ii) verification of the original project premises, including the analysis of gaps to identify additional requirements imposed by current norms;

(iii) the safety coefficients;

(iv) the properties of the materials of the system components;

(v) the loads in action on the system; ·

(vi) the calculated stresses; and

(vii) the current operational conditions of the system.

Based on the calculated RPN, the subsystems were classified as less sensitive to ageing, moderately sensitive to ageing and highly sensitive to ageing, as shown in the Table 1.18.

Table 1.18 - Prioritization of SSC

Item under evaluation	Component type	Classification - RPN
1	PIG launcher	Less sensitive to ageing
2	Surface pipes	
13	Closing spool (emerged)	
14	Surface pipes	
15	PIG receiver	
3	Rigid spool (submerged)	Moderately sensitive do ageing
6	Rigid stretch	
7	Rigid stretch	
8	TIE-IN	
9	Manifold	
10	TIE-IN	Highly sensitive to ageing
11	Rigid stretch	
4	Flexible riser	
5	Flexible riser	
12	Flexible riser	

Source: The author, 2024

The PIG launcher/receiver subsystems (items 1 and 15), surface pipes (2 and 14) and the emerged closing spool (13) were categorized as less sensitive to ageing, mainly because of the greater probability of detection of their failure modes due to not being submerged and hence having the surveillance/procedures of topside teams.

Thus, these items (1, 2, 13, 14 and 15) were considered non-priority (non-critical elements) and consequently were excluded from subsequent steps in the framework.

1.4.2.4.4 Assessment of current condition.

Since the items listed as 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 were considered critical, their current integrity condition (current physical and functional health status of an asset) was assessed.

The integrity assessment was based on the history of tests and monitoring performed during the entire operational life of each subsystem/component, and especially on the results of the last inspections. The evaluation was guided by the integrity management process and the indicators defined by the operator, including visual inspections by a diver and by the remote method with remote-operated vehicle (ROV), inspections by instrumented PIG, measurements of helical torsion and deformation of the tubular body, measurements of thickness, cathodic protection inspections, including electrochemical potential measurement and assessment of free spanning pipelines.

With respect to the manifold (item 9), it was evaluated with a main focus on erosion issues, and it was found that there was no relevant amount of sand in export fluids, so the equipment will not be affected by the erosion failure mechanism.

As discussed, and proposed in section 1.3.4.4, considering the aforementioned information and the qualitative condition classification matrix presented by Animah and Shafiee (2018), the categorization of each of the critical items (3, 4, 5, 6, 7, 8, 9, 10, 11 and 12) was obtained according to Table 1.19.

Table 1.19 - Components categorization table

Class	Description	Items identified
Poor	The condition of the subsystem or component is significantly outside design limits and should be discarded.	None
Uncertain	The condition of the subsystem or component may be outside design limit or unknown and RUL must be determined	Items 3, 4, 5, 6, 7, 11 and 12
Good	The condition of the subsystem or component is within design limit and RUL do not need to be determined	Items 8, 9 and 10.

Source: The author, 2024

Therefore, considering the proposed guidelines, the components in the green zone above may be eligible for extension. Components in the yellow category must proceed to the next step proposed in the guidelines to confirm their qualification for the extension of their useful life, a stage in which each component will have its RUL evaluated to reduce the level of associated risk.

1.4.2.5 Assessment of remaining useful life (RUL)

Based on the information from the design and from the operational phase, listed in 1.4.2.4.1, and on the assessment of the characteristic failure mechanisms, associated with the main failure modes of each of the components of the subsea production system, the RUL for the items 3, 4, 5, 6, 7, 11, and 12 was estimated considering the assessment of failure mechanisms and the physical failure mode prediction model, as summarized in Table 1.20.

Table 1.20 - Consolidation of the assessment of the current condition

Item under evaluation	Component Type	Evaluation	Result/RUL
3	Rigid spool (submerged)	Internal corrosion	**RUL = 1.8 years**
4	Flexible riser	Fatigue assessment	RUL (connector) > 5 years
			RUL (stiffener) > 5 yearsRUL
		Pressure sheath analysis	> 5 years
5	Flexible riser	Fatigue assessment	RUL (TDP) > 5 years
		Pressure sheath analysis	RUL > 5 years
6	Rigid stretch	Fatigue assessment of free spanning pipelines	RUL > 5 years
		Internal corrosion	RUL > 5 years
7	Rigid stretch	Fatigue assessment of free spanning pipelines	RUL > 5 years
		Internal corrosion	RUL > 5 years
11	Rigid stretch	Fatigue assessment of free spanning pipelines	RUL > 5 years
		Internal corrosion	**RUL = 4.8 years**
12	Flexible riser	Fatigue assessment	**RUL (connector) = 3.2 years**
			RUL (stiffener) > 5 years
			RUL(TDP*) > 5 years
		Pressure sheath analysis	RUL (degradation by hydrolysis) > 5 years
			RUL (degradation due to extrusion by fluency) > 5 years

Source: The author, 2024

Furthermore, as defined and justified in the “Evaluation of asset condition” stage of the proposed guideline (see section 1.4.2.4.1), it was assumed, to determine the remaining useful life of the analyzed components, that the operational conditions will be maintained. Therefore, the results of the technical analyses are valid as long as there are no significant changes in the operational conditions considered in the analyses.

The estimate obtained from the calculation of the RUL was compared with the LE period intended by the operator. The RUL values below 5 years are highlighted in Table 1.20.

In the case of flexible risers, the fatigue assessment was established considering the areas close to three points along the pipeline: the connector, the bend stiffener and the touchdown point (TDP). Based on the geometry and characteristics of each riser, it is to be highlighted that:

(i) the one identified as item 4 in Table 1.20 does not have the TDP region;

(ii) the one identified as item 5 does not have the connector and stiffener area, and

(iii) the one identified as item 12 has the three areas mentioned.

Based on the assessments above, mitigating measures were defined to be adopted for those components with a RUL estimate lower than the period intended by the operator (5 years) so that they can be considered for LE.

1) The rigid spool (item 3) installed in the production facility (PLAT A), according to the internal corrosion criterion, had a remaining life of only 1.8 years.

Therefore, it was decided to replace it with a new spool. Until the exchange is implemented and considering that the component needs to be manufactured, a repair will be carried out by applying a composite material that will guarantee the operation of the component for another 2 years, which is the estimated time for the implementation of the replacement.

Thus, by considering the mitigating measure as definitive, a new estimate was performed which resulted in a RUL above 5 years.

2) The rigid section (item 11) connected to production facility B (PLAT B), according to the internal corrosion criterion, had a remaining useful life of 4.8 years, which is very close to the intended 5 years.

In view of that, it was decided to install a bandage with anticorrosion protection and structural reinforcement, and after recalculating the RUL, a remaining life above 5 years was obtained.

3) The flexible riser connector (item 12) attached to production facility B (PLAT B), according to fatigue assessment, had a remaining life of 3.2 years.

The failure mode associated with the fatigue of the tensile armors of the riser results in a gradual rupture that goes from the armor up to the failure, as observed in real scale tests and the failure history of the referred pipeline.

Hence its operational continuity for the 5 years period is subject to the definition of a differentiated inspection plan and monitoring so that possible signs of torsion in the flexible riser can be identified. Therefore, the recommendations for the RUL to reach the intended 5 years are:

- Install the monitoring system via MAPS technology on the riser under consideration and do the monitoring so as to continuously reassess the integrity of the pipeline;
- Implement differentiated inspection with shallow diving with differentiated periodicity (quarterly);
- Limit the top pressure of the riser to ensure that it does not stay above 40 kgf/cm^2 more than 10% of the time.

Based on the calculation of RUL and considering all mitigating measures being implemented, all the items analyzed move to the next stage of the framework.

1.4.2.6 Evaluation of obsolescence and organizational issues

Since the assessment of obsolescence and organizational issues was addressed in a preliminary manner in section 1.3.6 of this article and will be expanded and deepened in future studies, those issues were considered, in the hypothetical case, not relevant to the definition of the strategy for extending the useful life, in view of the following facts:

- Spare parts are readily available and are still being produced by the original manufacturers;
- There is a long-term agreement with the suppliers of spare parts for the components of the interconnection system between PLAT A and PLAT B, with provisions in place to assure a continuous supply throughout the period proposed for LE;
- The technology to be installed to monitor tension on flexible risers (MAPS technology) is fully compatible with the technologies of the interconnection system commissioning phase. The team has been well trained and has knowledge of this new technology;

- The differentiated inspections listed as recommendations for extending the remaining life of the riser are defined through the operator's execution operational procedure and these tasks are already routinely performed by qualified professionals;
- Regarding new regulations and requirements, in spite of the recent publication of Resolution ANP n º 41/2015 (ANP, 2015), which deals with operational safety requirements for the management of subsea systems, the company already has a strong management system in place, which complies with the requirements imposed by regulation;
- It is not expected, in the next 5 years, a significant portion of the workforce to be allocated to other facilities or to retire, considering the main leaders and team members. Therefore the skill set of the staff is expected to be preserved;
- The current facility operator is intent on remaining the sole operator of the asset, as it has been for the last 15 years;
- The company has management and execution standards closely aligned with the best international practices and a policy of continuous training of its employees in those standards;
- The company has a training policy that covers technical training and also the procedures for the performing of functions (this last training, in some cases, is done "on the job"); and
- The process for extending the life of the operator's assets is something that has been studied in recent years, and the company went through two similar experiences in the past. In this regard, the staff is aware of the risks and has experience in the LE process of offshore assets.

1.4.2.7 Definition of life extension strategy

Considering the conditions of each component of the subsea production system and that the assessment of obsolescence and organizational issues proved to be not relevant to the LE process of such system, the following table shows the strategies to be adopted for the asset, according to the classification detailed in Table 1.21 (Franklin *et al.*, 2008; Shafiee; Animah; Simms, 2016; Shafiee; Animah, 2017).

Table 1.21 - Consolidation of the LE strategy

Item under evaluation	Component type	Additional actions	LE strategy
1, 2, 4, 5, 6, 7, 8, 9, 10, 13, 14, 15	• PIG launcher; • Surface pipes; • Flexible riser (TR001); • Flexible riser (TR002); • Rigid stretch; • Rigid stretch; • TIE-IN; • Manifold; • TIE-IN; • Closing spool; • Surface pipes; • PIG receiver	None	Keep in place the strategy adopted during the operational life of the system
3	Rigid spool	Repair with application of composite material	Temporary repair
		Replace with a new spool	Replacement
11	Rigid stretch	Installation of bandage with corrosion protection and structural reinforcement	Repair
12	Flexible riser	Install the monitoring system via MAPS technology on the riser under consideration and monitor it via MAPS	Refurbishment
		Implement differentiated inspection with shallow diving with differentiated periodicity (quarterly)	Reconditioning
		Limit the top pressure of the riser so that it will not stay above 40 Kgf/ cm^2 more than 10% of the time	Reuse

Source: The author, 2024

1.4.2.8 Assessment of economic issues

From an economic viewpoint, the following information was taken into consideration for an incremental assessment of the cost/benefit ratio associated with the intended useful LE:

- the profit margin on the production of the asset (facilities A and B and the subsea production system) stands currently at 30%;
- the total costs associated with the subsea production system throughout its operational life are split into 50% of capital cost, 30% of installation cost and 20% of operating cost;
- it is estimated that the actions to be taken due to the extension of the asset's life, considering the additional 5 years of operation, have an impact of 10% in the

capital cost, 5% in the installation cost and 5% in the operating cost, totalling a cost increase of approximately 7.5%; e

- it is estimated that production will not significantly decrease in the next 5 years of operation.

So, from the economics viewpoint, the profit margin will be impacted by around 7.5%, which can be considered attractive for this type of business and for the size and standing of the asset operator. This cost increase is also considered insignificant when compared to the cost associated with installing a new subsea production system.

On top of this, there is the intangible fact that the postponement for 5 years of the costs associated with decommissioning is beneficial for the operator, since the Brazilian industry will be more experienced in this type of activity and will be able to rely on a greater offshore and onshore structure to support this stage of the installation life cycle.

1.4.2.9 Definition of a life extension management plan

The LE Management Plan consists of the document that presents the results of the main previous steps of the framework, systematizing the way of managing the LE of the asset. It must be elaborated before the implementation of the extension process. This plan includes:

- Results summarizing the technical assessment of the asset and a list of mitigation measures ranked to reduce risk during the technical assessment, as presented in the steps of section 1.4.2.4 of the case study;
- Overview, as well as premises and limitations, of the decisions taken during the process of defining the LE strategy, as presented in the steps in sections 1.4.2.1, 1.4.2.2 and 1.4.2.3 of the case study;
- The measures that will be adopted to guarantee the availability of spare parts and also guarantee the retaining of the knowledge and experience acquired by the operator, as presented in section 1.4.2.6 of the case study; and
- Statement of the adopted strategy for each SSC analyzed, presented in section 1.4.2.7 of the case study.

Additionally, it presents the details of the issues related to integrity management and the specification of indicators to monitor the effectiveness of the Plan to be implemented.

With regards to the management of the integrity of the subsea production system, the mitigating measures and the defined strategies can be systematized as follows:

- Registration of inspection/maintenance plans or maintenance/service orders, as summarized in Table 1.22, in the integrity management system adopted by the operator.
- The elaboration of procedures for the operation of the system will be defined and new training requirements for those procedures will be generated, as summarized in Table 1.22.

Table 1.22 - Integrity management

Item under evaluation	Component type	Integrity management	Implementation procedures	Training
1, 2, 4, 5, 6, 7, 8, 9, 10, 13, 14, 15	• PIG launcher; • Surface pipes; • Flexible riser (TR001); • Flexible riser (TR002); • Rigid stretch; • Rigid stretch; • TIE-IN; • Manifold; • TIE-IN; • Closing spool; • Surface pipes; • PIG receiver	(1)	(2)	(3)
3	Rigid spool	Opening of service order to perform a repair with application of composite material	(2)	(3)
		Opening of a service order to replace the spool	(2)	(3)
11	Rigid stretch	Opening of service order for installation of bandage with anticorrosion protection and structural reinforcement	(2)	(3)
12	Flexible riser	Opening of service order for installation of monitoring system via MAPS technology.	Elaboration of operational procedure/ instruction for monitoring via MAPS	Develop training in the procedure/ instruction for monitoring via MAPS
		Change the periodicity of the	(2)	(3)

Item under evaluation	Component type	Integrity management	Implementation procedures	Training
		existing shallow diving inspection plan (from annual to quarterly).		
		(1) for the remaining inspections/tests planned for the riser.	Elaboration of operational procedure/ instruction for pressure monitoring.	Prepare training in the operational procedure/instruction developed

Note: (1) Keep in place inspection/test plans defined in the operator's management system. (2) Keep in place execution procedures already defined in the operator's management system. (3) Keep in place training already defined in the operator's management system.

Source: The author, 2024

Regarding the specification of indicators, the following was defined:

- indicators for monitoring the safety integrity of the rigid stretch components (item 11) and flexible riser (item 12). Indicators of detailed measurement results from inspections and tests have been created to monitor possible symptoms of ageing damage;
- indicators for monitoring of operational parameters to confirm that the assumption used to calculate the RUL, that current operational conditions would be maintained for the next 5 years, remain valid;
- indicators to verify if all mitigation measures established in the plan have been complied with and if deadlines have been respected;
- indicators to verify whether the mitigating measures established in the plan are sufficient to guarantee the safety and operation of the subsea production system through the intended period. As an example of indicators:
    - the results of visual monitoring and MAPS to confirm the condition of non-degradation of the tensile armors;
    - the results of bandage condition monitoring to confirm the condition of the rigid stretch.

1.4.2.10 Obtaining regulatory approval

After the elaboration of the LE Management Plan, it must be assessed whether it is in line with the existing regulations established by the regulatory body.

In Brazil, the current regulation associated with the system to be extended consists of Resolution ANP nº 41/2015 (ANP, 2015), which deals with operational safety management in subsea systems, and it was found that each of the requirements set by regulations was followed in the Plan and submitted to the appreciation of the regulatory body.

1.4.2.11 Implementation of life extension management plan

Upon approval by the regulatory body, the LE Management Plan is put into practice and incorporated into the operator's operational safety management system, taking into account all practices of such system, especially those related to integrity management, training, useful LE and safety culture.

1.4.2.12 Monitoring the life extension management plan effectiveness

To assess the level of effectiveness with which the operator is managing the subsea production system during the entire extended life period, the indicators defined in the LE Management Plan are monitored monthly and undergo a critical analysis by the asset's technical and management staff. In this sense, so far all indicators for the interconnection system between facilities A and B are in accordance with the established goals, and the LE remains on course.

From items 1.4.1 and 1.4.2, it is possible to establish a comparison, in terms of the details presented, between real cases submitted to the regulatory body and the hypothetical case, which followed the stages proposed in the framework. It can be inferred that even though they refer to different systems and, consequently, different complexities, the real cases have gaps in terms of organization, completeness and scope.

From the regulator's viewpoint, those gaps lead to a lack of understanding of the analyses performed, which support decision making, lack of clarity as to whether all aspects concerning the ageing process were considered and, consequently, difficulty in the approval process of the plans submitted by the operators.

From the operator's viewpoint, who in this case is the decision maker, the aforementioned gaps have an impact on the lack of systematization of their analysis process. This fact can, in principle, lead to difficulties and delays in carrying out technical analyzes and, in the end, lead to mistaken decisions in terms of economic and financial aspects and also in terms of operational safety.

1.5 Conclusions

The end of the life cycle of an SSC requires a decision-making by the operator. LE has been an attractive approach for the intensive capital industry, such as the oil and gas industry. From the LE of industrial assets, a wide range of economic, technical, social and environmental benefits can be obtained, when compared to the adoption of other life cycle management strategies, such as replacing the equipment or decommissioning.

This paper contextualized the application of the LE concept in Exploration & Production (E&P) in the oil and gas industry, showing data about the LE of assets in the North Sea (Norway and United Kingdom), in the Asia-Pacific region, (Malaysia and China), in the Middle-East, and in the Gulf of Mexico. Additionally, the scenario in Brazil was detailed, comprising the platforms and their respective subsea systems, showing the age and the expectation of the assets regarding LE in the next few years. The challenges of the ageing process are already notably a reality in the Brazilian context.

The article pointed out two ways to categorize the ageing process, depending on the author, and the challenges related to each of the categories. It showed that, although most of the literature focuses on material physical degradation, the impact of obsolescence and organizational issues in the decision about LE cannot be disregarded.

Afterwards, a review was done on the current state of the art about LE of assets in the oil and gas industry and in other industries, considering not only the scientific literature, but also documentation issued by local and international regulatory bodies. In this sense, it was observed that several stages that are part of the process for assessing the life cycle extension are addressed individually by several authors, and with a very interesting level of depth.

However, although absolutely relevant, those topics, when covered individually, do not allow an accurate analysis – or even a minimally adequate one – of the possibility of extending the life of an asset, which highlights the importance of proposing a structured analysis methodology.

In this sense, this article consolidates in stages this set of topics that is presented in the literature in an unstructured way, and then proposes a methodology (framework) for the development of a process for the management of the useful LE in a broad and systematic way, contributing to the decision-making procedures regarding the LE of a facility or system. To that end, theoretical principles are presented, based on the literature available, for each of the stages of the proposed methodology.

The proposed framework, which is an important contribution to the research on this field, is comprised of twelve stages detailed and subcategorized in a set of activities: (i) definition of LE motivation; (ii) definition of LE period; (iii) definition of LE premises; (iv) evaluation of asset condition; (v) assessment of RUL; (vi) evaluation of obsolescence and organizational issues; (vii) definition of LE strategy; (viii) assessment of economic issues; (ix) definition of a LE Management Plan; (x) obtaining regulatory approval; (xi) implementation of LE Management Plan and (xii) monitoring the LE Management Plan effectiveness.

The importance of this structure in stages is highlighted with the presentation of three case studies. These cases studies were conducted regarding different offshore production facilities, comparing the information in their LE processes submitted to Brazilian National Oil and Gas Agency and the proposed framework shown by this article. Concisely, it can be highlighted that the operators focus their analyses on technical aspects, mainly regarding material degradation, and do not assess the obsolescence and organizational issues, do not show economic assessments or show clear strategies they intend to adopt.

Considering the gaps in real cases in terms of organization, completeness and scope, the methodology proposed in this article was applied to a hypothetical case, based on facts reported by a major operator in Brazil. As a result, following all the stages proposed by the framework, it was possible to determine that the use of the proposed methodology transformed the assessment of the possibility of extending the life of an asset into a systematic and transparent process, resulting in easier and better-founded decision-making procedures. In addition, it has been demonstrated that the application of the methodology also improves the management of the asset during its extended life.

In this article, the obsolescence and organizational issues were assessed with preliminary approach. Thus, the continuation of this research, should broadened and deepened these approaches.

2. OBSOLESCENCE MANAGEMENT FOR OFFSHORE OIL AND GAS PRODUCTION FACILITY LIFE EXTENSION

The extension of the service life of offshore oil and gas production facilities has been an object of increased interest because of its benefits. In previous work, the authors proposed a guideline for managing the life extension process of oil and gas facilities, however without integrating obsolescence management. The main objective of the present study consists of developing a framework to guide the evaluation and management of asset obsolescence in the context of life extension, considering the concept of obsolescence as having four types of drivers - unavailability from manufacturers, new requirements or demands, technological or technical changes, and new conditions or needs. A framework with six stages of obsolescence management process was proposed and validated with a case study. Because no single request submitted to the Brazilian oil and gas regulator of a facility considering life extension had complete information to perform the obsolescence evaluation, a hypothetical case study was developed with a combination of information from real offshore production facilities. Results demonstrate that the framework: transforms the assessment and management of obsolescence into a systematic process that identifies priority impacted elements and, based on the risks associated with their obsolescence, supports the definition of the most appropriate decision.

2.1 Introduction

According to Wintle *et al.* (2006), plant ageing is not characterized solely by the age of the equipment. Ageing also comprises the condition of the equipment and how it changes over time. As equipment ages, operating conditions approach established safe limits, processes change, and more frequent advanced inspection techniques are required. In this phase, major repairs may also be needed and accelerated deterioration may occur (Wright, 2011).

Nevertheless, the effects of ageing are far more comprehensive than just the material physical degradation. Hokstad *et al.* (2010) classify the ageing process into three main areas: (i) material degradation (physical damage), (ii) obsolescence, which includes issues related to outdated equipment, introduction of new technologies, existence of new requirements, and/or regulations and new needs, and (iii) issues related to the organization.

Most of the literature focuses on material physical degradation (Tan; Lu; Zhang, 2016; Soleimani; Campean; Neagu, 2020). In this context, some authors define optimal end-of-life (EOL) management based only on the evaluation of material physical degradation (Liu; Frangopol, 2020). Others deem "obsolescence" to be synonym to ageing (FAM *et al.*, 2018). However, obsolescence and organizational issues are also dynamic and must be assessed as part of ageing management (Hokstad *et al.*, 2010; Aeran *et al.*, 2017; Ferreira *et al.*, 2020).

Indeed, for certain types of systems, such as control and instrumentation, the leading cause of reaching the end of life is obsolescence. Control and instrumentation systems can be reliable for a long period, provided maintenance is performed correctly (Conn *et al.*, 2010). However, such maintenance can only be properly performed if there is a support service and availability of spare parts (Paska *et al.*, 2007). When it becomes unavailable – which happens often -–, the component becomes obsolete which will be further detailed in the next section of this article.

Obsolescence is not tied to the age of the equipment (Lane *et al.*, 2012). As highlighted by Akbar *et al.* (2015), obsolescence can impact equipment at all stages of its life cycle. In avionic defense systems, 70 - 80% of electronic components become obsolete before they are even used in the field. Obsolescence can arise even before the end of the development phase. Thus, obsolescence must be managed from the initial phases of a project (Romero Rojo *et al.*, 2010).

Nevertheless, the risk of Systems, Subsystems, and Components (SSC) obsolescence is greater when the asset is ageing. Previous authors have sought to predict the probability of obsolescence (Trabelsi et.al., 2021; Christina; Olson; Summers, 2021), considering a time horizon. The Nuclear Utility Obsolescence Group found in 2004 that 11% of interviewed experienced losses in energy generation in their plants, due to obsolescence. In 2007, this number increased to 22% (Pragale *et al.*, 2016). Nevertheless, in France, with exceptional maintenance and inspection programs, equipment obsolescence has been successfully managed as all nuclear power plants have reached a service life of at least 40 years old, without detriment to the level of safety (Hedin, 2008).

In the oil and gas Exploration and Production (E&P) sector, assets remain in operation for more than 20 years, over which period technology changes, regulatory and standards frameworks evolve, availability of spare parts decreases, technical support services become scarce and new operational conditions are introduced in the process, among other challenges. These issues can cause new risks to assets, people, and the environment, and must be managed. Obsolescence issues have become increasingly frequent in the oil and gas industry. Several producing fields in the world have reached a stage where upgrading obsolete control and automation systems can be considered too high, leading to early production interruption (Baker, 2011).

2.1.1 Life extension and obsolescence

As an asset ages and reaches its expected useful life, the operator must demonstrate that this asset can continue to be safely operated if operations are to be extended beyond this useful life. According to Hokstad *et al.* (2010), the operator must guarantee the technical, operational, and organizational integrity of the installation throughout the extended life period.

Because the frequency of obsolete items increases during life extension, at a systems level, ageing issues compound (Electric Power Research Institute, 2008). Although the risk of obsolescence for electronic and electromechanical items is greater, obsolescence management should be performed for all types of SSC, as part of the life extension process. Tartt et. al (2021), for example, include obsolescence issues within the assessment of material degradation in wind turbine life extension.

A systematic review of the literature was completed, following the methodologies of Wright, *et al.* (2007) and Antunes and Pinheiro (2019). A search in the Scopus database of the term “obsolescence” in conjunction with various synonyms for “extension of service life of assets” (“life extension”; “ageing”; “aging”; “lifecycle extension”; “extended life”; “safety”; “aging management”; “ageing management”) yielded 604 results. These were further filtered to the engineering area, returning 310 references. All titles and references were analyzed with the softwares VOSviewer and NVivo. This analysis showed that the number of publications focusing on obsolescence within life extension has increased over the last few decades, particularly since the 2000s. This increase was motivated by the energy sector’s needs to maintain the operation of aged assets, reducing capital expenses; and delaying the decommissioning of assets as much as possible (Wright, 2011). Additional drivers for the oil and gas industry, are to increase the recovery factor of mature fields, and maintain operational safety, avoiding incidents due to loss of containment in the old facilities.

Furthermore, regarding the term “obsolescence management”, articles related to the oil and gas industry usually: (i) approach the issue of obsolescence mainly at the equipment level, lacking a more in-depth examination into the effects of this kind of ageing on systems and components; (ii) are limited to the effects of obsolescence caused by technological changes and are associated with availability or support from manufacturers; (iii) concentrate more on the risks related to inventory maintenance, while dedicating little attention to the risks associated with obsolescence in terms of the safety and reliability of the asset.

While “obsolescence management” is mentioned, there are no prescriptive studies, detailing the proper identification, analysis, and management of obsolescence or that are conducted in a structured and systematic manner during the phase of the extension of the assets’ service life. Ferreira *et al.* (2020) proposed a guideline for planning the life extension of offshore oil and gas facilities. While obsolescence and organizational issues are mentioned, they are not described in detail as part of the framework.

2.1.2 Scope of paper

The present work seeks to develop an obsolescence management approach as part of offshore oil and gas production facility life extension. This objective will be achieved by: (i) developing an obsolescence assessment framework, and (ii) modifying the definition of LE strategy and management plan accordingly. Both of these sub-objectives extend upon the work of Ferreira *et al.* (2020). The first will define stages for the “Evaluation of obsolescence and organizational issues” and the second will modify the “definition of life extension (LE) strategy, assessment of economic issues” and “definition of a LE Management Plan”, stages proposed by Ferreira *et al.* (2020).

It should be noted that the purpose of the present paper is not to develop each stage of the obsolescence assessment framework, as individual stages have already been addressed in depth by previous authors (Szoch; Brown; Wilkinson, 1995; Paska *et al.*, 2007; Electric Power Research Institute, 2008; Norwegian Oil Industry Association, 2008; Al-qahtani *et al.*, 2010; Hokstad *et al.*, 2010; Bounds, 2011; Håbrekke *et al.*, 2011; Romero Rojo *et al.*, 2012; lane *et al.*, 2012; Al-qahtani *et al.*, 2012; Schoeckle; Rothenhoefer; Koenig, 2014; Tveit;

Sivertsen; Hernæs, 2014; Belshaw, 2015; Pragale *et al.*, 2016; Memuletiwon *et al.*, 2017; Yu *et al.*, 2017; Anwar, Pudjiantoro; Bahroinuddin, 2018; Ferreira *et al.*, 2020). While considering the stages in isolation is useful in detailing specific methods, previous studies do not portray a holistic or accurate analysis of obsolescence of extending the life of an asset. Therefore, the paper combines approaches presented in the literature in an unstructured way, and consolidates them in stages, proposing a methodology (framework) for the evaluation of obsolescence.

To this end, Section 2.1 presents an introduction, situating obsolescence management within ageing management and life extension. Section 2.2 establishes a conceptualization of obsolescence, and identifies the main impacts of obsolescence. Section 2.3 presents the proposed methodology for evaluating obsolescence and describes the case study on which it was applied. Section 2.4 describes the results of the case study application. Finally, Section 2.5 brings the conclusions of the work, discusses the implications for applying the framework to other cases, and suggests future areas of research.

2.2 Obsolescence - Concepts and impacts

Obsolescence has been defined differently by previous authors. This section presents the concepts of the different types of obsolescence, as well as their expected effects. This set of concepts grounds the development of this article.

Memuletiwon *et al.* (2017) and Akbar *et al.* (2015) define the terms Obsolescence, Obsolescence Management, Obsolescent, and Obsolete as follows: (i) Obsolescence - the transition period between the availability of the SSC from the original manufacturer until its complete unavailability; (ii) Obsolescence management - Strategies for identifying the effects and risks associated with the obsolescence of a SSC and for defining actions to mitigate them during the entire life cycle of an asset; (iii) Obsolescent - Period in which the SSC is subject to the announcement of the original manufacturer regarding the end of production or the provision of the service; and (iv) Obsolete - Although SSC may be available in the supply chain, it is no longer available from its original manufacturer.

The obsolescence period begins immediately after the manufacturer signals the end of production. The SSC is considered obsolete when there is a gradual reduction in production volume by the original manufacturer until the point when it is no longer technically supported or is not commercially available by the Original Equipment Manufacturer / Supplier (OEM / OES), despite still being in the supply chain. (Akbar *et al.*, 2015; Memuletiwon *et al.*, 2017). Pragale *et al.* (2016) further expand this definition to encompass the issue of the unavailability of the support service from the original manufacturer or the difficulty in acquiring and qualifying support from new suppliers.

However, obsolescence is not restricted to the issue of SSC availability and service support by the manufacturer, also known as obsolescence related to Diminishing Manufacturing Sources and Material Shortages (DMSMS) (Anghel *et al.*, 2003; Konoza *et al.*, 2014; Belshaw, 2015). Obsolescence in this article also encompasses three other challenges: new requirements or demands, technological changes, and new conditions and/or new needs.

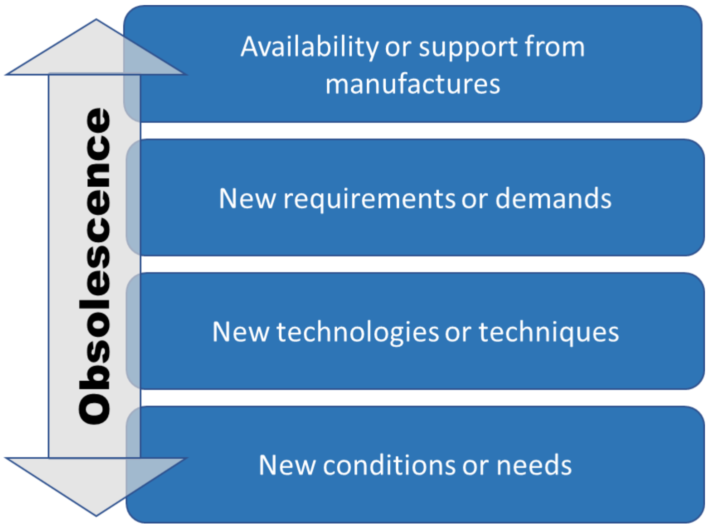
Obsolescence caused by new requirements or demands is characterized when specific requirements for a given SSC are changed, making its function or performance outdated (Belshaw, 2015). New requirements may have been altered by external regulatory changes (factors outside the organization to which the SSC belongs), such as requirements of technical norms/standards, directives issued by regulatory bodies, and industry criteria or good practices (International Atomic Energy Agency, 2014). Internal changes to technical norms, philosophies, performance standards of equipment or functions, or other internal requirements may also be the culprit. Hence, the fact is that regardless of what motivated the introduction of changes, the SSC no longer complies with the regulations or criteria currently valid.

Obsolescence caused by technological changes is brought upon by technological evolution, i.e. technology becomes outdated for technical, legislative, and/or market reasons (Song; Zipkin, 1996). These reasons are not necessarily related to the past or current performance of the SSC, but will likely influence its future use. Four solutions to technological obsolescence can be adopted by a company (Borgonovo; Marseguerra., 2000; Amankwah-Amoah, 2017): (1) discontinue the use of the old technology and its SSC altogether; (2) discontinue the use of the old technology by incorporating the new technology to keep the SSC in operation; (3) keep the old technology and its SSC in operation without incorporating the new technology, or (4) combine old and new technologies. In some cases, it might not be possible to incorporate new technology within an existing SSC. Feldman and Sandborn (2008), Amankwah-Amoah (2017) and Zolghadri *et al.* (2018) highlight that technological obsolescence can be caused by the incompatibility between SSC and constituent technology life cycles, as the technologies may have shorter life cycles than the SSC itself.

Obsolescence caused by new conditions and/or new needs is very similar to a loss of functionality. This is not due to initial design errors or poor condition, but rather due to new expectations that the asset was never intended to meet. For example, changes to the processing plant may require the SSC to work away from its operating envelope, leading to possible unsafe conditions or poor performance.

Each of these types of obsolescence may have intersections. For example, a SSC may initially be technologically obsolete when the given technology is no longer applied, and later also experience DMSMS obsolescence. Based on the types of obsolescence defined above, the present study conceptualizes obsolescence as a combination of factors, as shown in Figure 2.1.

Figure 2.1 - Conceptualization of obsolescence and its drivers



Source: The author, 2024

The impacts of obsolescence vary by type. When there is no availability or support from manufacturers, issues largely arise at the time of failure. This challenge may have been signaled earlier when similar SSC failures occurred if it was already difficult to acquire spare parts. If at the time of failure, no support or spare parts are available, there can be significant downtime as solutions are sought. An alternative SSC may need to be qualified or tested before being applied, which can increase costs and result in a significant loss of production (Akbar *et al.*, 2015).

Besides the issues of operational unavailability and downtime, obsolescence caused by DMSMS can affect the maintenance of the SSC, especially those with a long operational life cycle (Zolghadri *et al.*, 2018). According to the Electric Power Research Institute (2008), DMSMS can lead to an increase in postponements of Preventive Maintenance (PM) tasks, unavailability of safety systems (Bounds, 2011; Schoeckle; Rothenhoefer; Koenig, 2014), corrective maintenance, urgent modifications, and Operation and Maintenance (O&M) costs.

Technological obsolescence, in turn, can cause greater difficulty in interfacing with other technologies available in the process, since the simultaneous adoption of new and obsolete technologies can generate compatibility difficulties (Pragale *et al.*, 2016). In addition, the older technology limits the possibilities of adding new features that would be beneficial to the systems and interfaces of the plant (Naser; Morris, 2004).

When obsolescence is caused by new requirements or demands or by new conditions or new needs, it does not occur at the time of failure. Instead, it affects the functionality of the SSC; i.e. the current function, performance, or reliability of the product becomes unsustainable. If this obsolescence is not adequately managed, it could impact safety (International Atomic Energy Agency, 2014; Schoeckle; Rothenhoefer; Koenig, 2014) Regardless of the cause for obsolescence, the main objective should be to operate the SSC safely and reliably (Pragale *et al.*, 2016). Unlike physical degradation, obsolescence is external to the SSC and does not derive from its nature or performance. In this sense, it is the effect impact of obsolescence that needs to be managed.

2.3 Materials and methods

This section presents the proposed obsolescence assessment framework (subsection 2.3.1) and modifications to the life extension management plan (2.3.2), as well as the case study (2.3.3) to which these proposed methods were applied.

Memuletiwon *et al.* (2017) and Romero Rojo *et al.* (2012) proposed seven main stages for obsolescence management: database development and improvement; assessment of associated risks; prioritization of the risks; selection of the most appropriate obsolescence strategy; development of the obsolescence management plan; execution of this plan; and monitoring of obsolescence. Based on these seven stages and further review of the literature, a detailed six-stage obsolescence assessment is proposed herein, summarized in Figure 2.1 and Table 2.1.

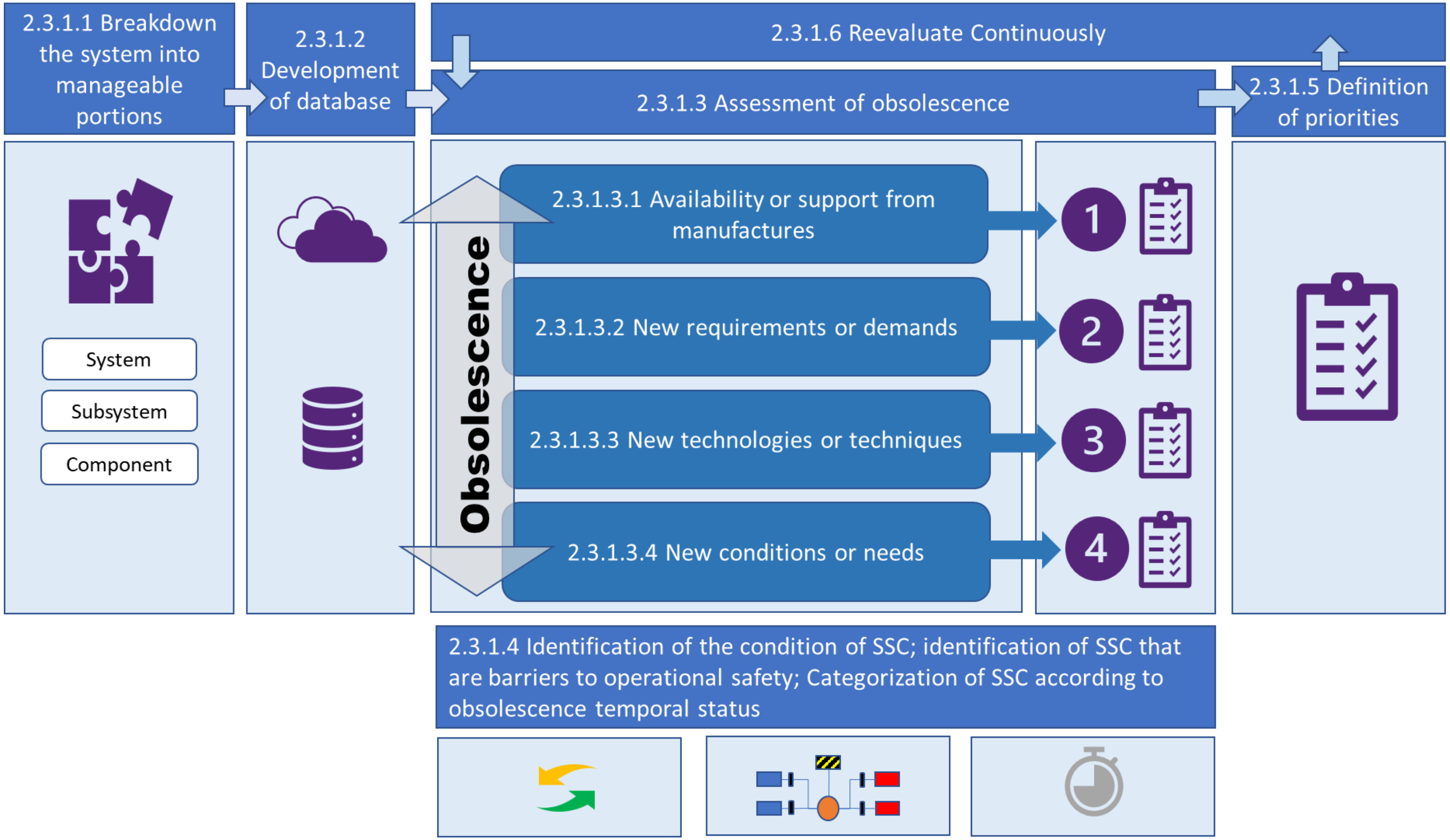
2.3.1 Main stages proposed for evaluating obsolescence

The six stages proposed for evaluating obsolescence are represented in the framework in Figure 2.2. The numbers in Figure 2.2 correspond to the subsections herein that describe each stage: (2.3.1.1) breaking down the systems into manageable portions; (2.3.1.2) developing a database; (2.3.1.3) assessing obsolescence; (2.3.1.4) identifying the condition of the SSC; identifying SSCs that are also operational safety barriers; and categorizing SSC according to the obsolescence temporal status; (2.3.1.5) defining priorities, and (2.3.1.6) reassessing in a periodical manner.

While the two initial stages are proposed as part of the evaluation of asset condition in the life extension framework of Ferreira *et al.* (2020), these activities must be extended upon in obsolescence management. The evaluation of obsolescence may require a more detailed breakdown of assets and additional information that would not necessarily be useful in the earlier assessment of material degradation.

The third stage (2.3.1.3) evaluates obsolescence in detail according to the four drivers defined earlier in Figure 2.1, namely: availability or support from manufacturers; new requirements or demands; new technologies or techniques, and new operational conditions or needs. The next stage (2.3.1.4) compliments the evaluation of obsolescence (2.3.1.3) and together provide inputs for the definition of priorities (2.3.1.5). The last stage ensures there is a continuous reevaluation of obsolescence (2.3.1.6), making the evaluation of the obsolescence process both dynamic and systematic throughout the extended life of the asset.

Figure 2.2 - Evaluation of Obsolescence Framework



Source: The author, 2024

Table 2.1 - Stages of the evaluation of obsolescence

Sections/ Subsections in this paper	Stages	Summary/Description	References
2.3.1.1	Breaking down the systems into manageable portions	Split systems and subsystems at the component level to facilitate the evaluation of obsolescence and, subsequently, the concentration of efforts.	Romero Rojo *et al.* (2012).
2.3.1.2	Development of a database	Gather basic information needed for the four types of obsolescence as a starting point for subsequent stages.	Paska *et al.* (2007); Hokstad *et al.* (2010); Al-Qahtani *et al.* (2010); Romero Rojo *et al.* (2012); Belshaw (2015); Memuletiwon *et al.* (2017); Yu *et al.* (2017).
2.3.1.3	Assessment of obsolescence	Evaluate obsolescence according to different potential drivers, accounting for the time intended to operate the SSC beyond its service life.	Romero Rojo *et al.* (2012).
2.3.1.3.1	Assessment of availability or support from manufactures	Assess the availability of spare parts and service provision for the SSC during the intended life extension and identify gaps.	Paska *et al.* (2007); Electric Power Research Institute (2008); Al-Qahtani *et al.* (2010); Hokstad *et al.* (2010); Håbrekke *et al.* (2011); Romero Rojo *et al.* (2012); Belshaw (2015); Memuletiwon *et al.* (2017); Anwar, Pudjiantoro and Bahroinuddin (2018); Ferreira *et al.* (2020).
2.3.1.3.2	Assessment of the impact of new requirements or demands	Assess the impact of new requirements or demands on installed SSC during the intended life extension and identify gaps.	Norwegian Oil Industry Association (2008); Hokstad *et al.* (2010); Lane *et al.* (2012); Tveit, Sivertsen and Hernæs (2014); Pragale *et al.* (2016); Ferreira *et al.* (2020).
2.3.1.3.3	Assessment of the impact of new technologies or techniques	Assess the impact of new technologies or techniques associated with installed SSCs during the intended life extension and identify gaps.	Norwegian Oil Industry Association (2008); Hokstad *et al.* (2010); Lane *et al.* (2012); Håbrekke *et al.* (2011); Pragale *et al.* (2016); Ferreira *et al.* (2020).
2.3.1.3.4	Assessment of the impact of new conditions or needs	Assess the impact of new operational conditions or new needs on SSCs during the intended life extension and identify gaps.	Hokstad *et al.* (2010); Håbrekke *et al.* (2011); Ferreira *et al.* (2020).
2.3.1.4	Identification of the condition of SSC; identification of SSC that are also barriers to operational safety and categorization of SSC according to obsolescence temporal status.	Identify in the lists of SSC the obsolescence category in terms of material degradation; those that are operational safety barriers according to a risk study; and the obsolescence temporal status – current obsolete, projected near-term obsolescence or projected long-term obsolescence – based on the intended life extension.	Szoch, Brown and Wilkinson (1995); Paska *et al.* (2007); Electric Power Research Institute (2008); Norwegian Oil Industry Association (2008); Electric Power Research Institute (2008); Bounds (2011); Lane *et al.* (2012); Schoeckle, Rothenhoefer and Koenig (2014); Yu *et al.* (2017); Ferreira *et al.* (2020);
2.3.1.5	Definition of priorities	Based on four lists of SCCs to each one of the four aspects	Norwegian Oil Industry Association (2008); Electric

Sections/ Subsections in this paper	Stages	Summary/Description	References
		mentioned in Figure 2.2, identify those with risk-based priority.	Power Research Institute (2008); Hokstad *et al.* (2010); Al-Qahtani *et al.* (2010); Håbrekke *et al.* (2011); Lane *et al.* (2012); Romero Rojo *et al.* (2012); Tveit, Sivertsen and Hernæs (2014); Akbar *et al.* (2015), Pragale *et al.* (2016); Belshaw (2015); Memuletiwon *et al.* (2017); Yu *et al.* (2017); Ferreira *et al.* (2020).
2.3.1.6	Reevaluate continuously	Periodically monitor and review items considered as non-priority, identifying whether any SSC has become critical to the operation.	Electric Power Research Institute (2008); Hokstad *et al.* (2010); Romero Rojo *et al.* (2012); Memuletiwon *et al.* (2017).

Source: The author, 2024

2.3.1.1 Breaking down the systems into manageable portions

Splitting a complex system into manageable units facilitates the analysis of the availability of each individual component and its potential impacts on the reliability and availability of the system to which they belong (Ferreira *et al.*, 2020, Khan; Haddara, 2004, Haddara; Khan; Krishnasamy, 2008). This process helps decision makers to identify those that are priorities and then to focus their resources and efforts. As indicated by Romero Rojo *et al.* (2012), the level of detail and stratification of SSC should be the lowest which makes the evaluation practical and possible. This decision is generally left at the discretion of what the authors called the Obsolescence Manager, which is the person responsible for the process of assessing the obsolescence of the asset.

2.3.1.2 Development of a database

To evaluate obsolescence according to the four drivers defined in Figure 2.2, relevant information must be collected, in addition to data already collected for the assessment of material degradation. Although the set of data required is quite distinct for each type of obsolescence, some information is common to all, such as (i) Description and application of the SSC in the process to which it belongs (Belshaw, 2015; Memuletiwon *et al.*, 2017; Paska *et al.*, 2007; Romero Rojo *et al.*, 2012; Yu *et al.*, 2017); (ii) SSC location (Belshaw, 2015); (iii) Plant Operation and Maintenance (O&M) data and (iv) Historical data on the management of changes in the SSC occurred during the operational life of the asset Specific information for each of the different causes of obsolescence is presented in the subsequent subsections.

2.3.1.3 Assessment of obsolescence

In the following subsections, the evaluation of obsolescence is presented for each of the four types: availability and support from manufacturers, new requirements or demands, new technologies or techniques, and new operational conditions or needs, as conceptualized in Figure 2.2. Each evaluation is based on the intended life extension of the asset and follows a set of questions, elaborated herein to identify obsolescence issues highlighted by Ferreira *et al.*, (2020) and Hokstad *et al.*, (2010). Questions were arranged to systematically identify the SSC most impacted by each obsolescence type.

2.3.1.3.1 Assessment of obsolescence in terms of availability or support from manufacturers (caused by DMSMS)

The information necessary to assess DMSMS is related to the plant and the SSC itself, and both the original and additional suppliers, including (i) Product name, model/part number and quantity installed in the plant, the original manufacturer (Memuletiwon *et al.*, 2017); (ii) Number of existing suppliers, historical rate of SSC utilization, availability of spare parts at manufacturers (Romero Rojo *et al.*, 2012) and at the operator (Belshaw, 2015); (iii) Time estimated for the end of supply or support by the original manufacturer (Belshaw, 2015; Hokstad *et al.*, 2010 and Paska *et al.*, 2007); and (iv) Issues associated with ease of maintenance of the SSC.

Based on the information collected, the list of SSC should undergo an examination of DMSMS obsolescence issues as proposed in Table 2.2. Questions were developed based on the issues identified by Ferreira *et al.* (2020) and Hokstad *et al.* (2010).

Table 2.2 - Proposed questions to assess DMSMS obsolescence

	Proposed questions
Outdated equipment	(1) Does the SSC reliability remain over time? (2) Does the SSC have a standard design (open architecture, standard connectors, modular)? (3) During the intended life extension... (a) Are spare parts readily available, without the risk of becoming in short supply? (b) Is technical support readily available, without the risk of lack of support in the period? (c) Are there companies able to supply spare parts? (d) Are there companies able to provide services? (e) In case of unavailability, can other maintenance and modification plans be identified? (f) Can the SSC be readily serviced? (g) In case of unavailability of spare parts, are they easy to reverse-engineer? (h) When performing repairs to the SSC, is it possible to introduce further damage? (i) Is it possible for the SSC to deteriorate due to the storage environment? (j) Are there long-term agreements already signed with suppliers for providing spare parts, reallocating parts, and developing structures or equivalent components, as well as for vendor support? (k) Is the expected demand for spare parts and provision of support services for each SSC compatible with the availability of spare parts and support services against the demand identified? (l) If supplier support is no longer available, can responsibilities for servicing be transferred to a different supplier?

Source: Adapted from Ferreira *et al.*, 2020; Hokstad *et al.*, 2010

In addition to the aforementioned issues, to prioritize the SSCs most impacted by obsolescence, it is also necessary to: (i) anticipate the expected demand for spare parts and support services provision for each SSC (Electric Power Research Institute, 2008) during the intended life extension of the asset; (ii) compare the availability of spare parts (Hokstad *et al.*, 2010; Håbrekke *et al.*, 2011; Anwar, Pudjiantoro; Bahroinuddin, 2018) and support services in face of the identified demand, and (iii) identify the gaps.

2.3.1.3.2 Assessment of the impact of new requirements or demands

To assess the impact of new requirements or demands, information should be collected on the latest revisions to standards, norms, regulations, and requirements relevant to the SSC. These revisions include but are not limited to: (i) changes in the safety philosophy of the operator; (ii) changes in performance standards (Hokstad *et al.*, 2010; Tveit; Sivertsen; Hernæs, 2014); (iii) new environmental requirements; (iv) new operational safety requirements; and (v) new technical requirement for equipment. Given this collected information, the SSC list should be examined based on the questions in Table 2.3, defined according to issues identified by Ferreira *et al.* (2020) and Hokstad *et al.* (2010). So, to identify the SSC most impacted by this type of obsolescence, gaps must be evaluated between current requirements or demands and those defined in the original design or latest revision (Hokstad *et al.*, 2010; Ferreira *et al.*, 2020).

Table 2.3 - Proposed questions to assess obsolescence caused by new requirements or demands

	Proposed questions
New requirements or regulations	(1) During the intended life extension … (a) are the original standards/ regulations applied to the SSC or currently met by it still applicable? (b) have the changed standards/regulations been incorporated during the operational life of the SSC? (c) if there is a waiver in regulatory terms for the analyzed SSC, does that waiver remain valid? (d) is it possible to meet the new standards/regulations/requirements established?

Source: Adapted from Ferreira *et al.*, 2020; Hokstad *et al.*, 2010

2.3.1.3.3 Assessment of the impact of new technologies or techniques

To assess the impact of new technologies or techniques, the availability of new technological solutions in the market should be explored for each SSC. These new solutions are those that, a priori, could be beneficial to the operation and safety of a given SSC during its extended life.

Based on the information collected, the obsolescence evaluation is proposed to follow the questions in Table 2.4, according to the issues raised by Ferreira *et al.* (2020), Hokstad *et al.* (2010), Lane *et al.* (2012) and Pragale *et al.* (2016). The target SSCs most impacted by new technologies or techniques are defined by the gaps between currently applied and new technologies (Hokstad *et al.*, 2010; Ferreira *et al.*, 2020).

Table 2.4 - Proposed questions to assess obsolescence caused by new technologies or techniques

	Proposed questions
New technologies	(1) During the intended life extension… (a) Is there any new technology or techniques applied to the SSCs under analysis? (b) Is there a relevant positive impact from the introduction of the new technology or technique to the operation, in terms of safety, reliability, operation continuity, etc, compared to the previous technology? (c) Is there a relevant positive impact from the introduction of the new technology or technique to safety, compared to the previous technology? (d) In the event of the introduction of new technology in the SSC under analysis, would the adjacent SSCs be compatible, that is, would there be interface problems? (e) In the event of the introduction of new technology in the SSCs under analysis, would the consequences of having new and original SSCs in the installation be negative?

Source: Adapted from Ferreira *et al.*, 2020; Hokstad *et al.*, 2010

2.3.1.3.4 Assessment of the impact of new conditions or needs

The assessment of the impact of new conditions or needs relies on the identification of changes in the operational conditions of the plant that will be or are expected during the intended life extension.

The impact depends on whether the SSCs will operate according to parameters different from those of the original project or those currently in place at the plant. The evaluation of obsolescence is proposed to follow the questions in Table 2.5, based on the issues highlighted by Ferreira *et al.* (2020) and Hokstad *et al.* (2010). The SSCs most impacted by this type of obsolescence are those with the greatest gaps between current and new conditions or needs.

Table 2.5 - Proposed questions to assess obsolescence caused by new conditions or needs

	Proposed questions
New requirements or regulations	(1) Comparing the most recent project (considering the implementation of the modifications) with the one currently in place at the plant, do the new conditions increase complexity of SSC operation? (2) Comparing the most recent project (considering the implementation of the modifications) with the one currently in place at the plant, do the new conditions result in lack of space or difficulties in accessing the SSC? (3) During the intended life extension ... (a) Does the SSC currently in place at the plant meet, without any adjustments or changes, the new operational conditions, and new requirements? (b) Will the intended new operation result in a greater risk to the operation? (c) Will the intended new operation result in a reduction in the SSC reliability? (d) Will the intended new operation result in the need to change the layout of the plant in association with the SSC? (e) Will the intended new operation result in the need to increase the structural load in the unit?

Source: Adapted from Ferreira *et al.*, 2020; Hokstad *et al.*, 2010

2.3.1.4 Identification of the condition of SSC, identification of SSC barriers to operational safety and categorization of SSC according to obsolescence temporal status

As part of the life extension process, assets must have their physical condition and obsolescence impact assessed. Within the framework proposed by Ferreira *et al.* (2020), physical condition is assessed according to several criteria, such as operation condition, production loss, material degradation, cracking, and corrosion. The overall condition is then rated as green, yellow, or red, based on Ferreira *et al.* (2020).

The Remaining Useful Life (RUL) is then calculated based on the age of the asset, expected service life, and its condition. RUL is the main type of prediction in the physical assessment of assets (Soleimani; Campean; Neagu, 2020). RUL is either the time left before reaching the end of the expected service life or before the condition of an asset crosses a service level threshold.

However, the assessment and estimate of the Remaining Useful Life (RUL) of Ferreira *et al.* (2020) do not consider the SSC breakdown to the level of detail required to assess obsolescence. Therefore, an additional condition assessment stage is proposed herein to ensure the breakdown required for the obsolescence evaluation also contains information on the condition. The assessment of the SSC condition must consider information and parameters such as operational experience, including the average time between failures, history of corrective and preventive maintenance, including maintenance activities performed outside the established intervals, and deterioration of the equipment (Silva, 2016).

The identification of barriers to operational safety must compile all SSCs flagged in risk assessments at all stages: project design, installation, and operation (Norwegian Oil Industry Association, 2008). These SSCs are those that, when their reliability and performance decrease, impact asset safety. This impact could be within the SSC itself or on another dependent asset.

Given the assessment of obsolescence in stage 3.1.3, SSCs can be categorized according to their obsolescence status over time. Herein, four classes are proposed: obsolete (Paska *et al.*, 2007; Electric Power Research Institute, 2008), obsolescence predicted for the short term, obsolescence predicted for the long term (Szoch; Brown; Wilkinson, 1995), and negligible likelihood of obsolescence, i.e. beyond the long term. The timeline classification must consider the intended life extension. Thus, the definition of short and long term will differ according to the life extension period, the long term being the extent of the life extension period.

2.3.1.5 Definition of priorities

After identifying the SSCs impacted by obsolescence, there is a need to define priorities, since the number of SSCs that are or will become obsolete during the extended life may be quite large. It is unreasonable to consider that operators will be able to proactively deal with all the items that may become obsolete. The Pareto Principle (Rule 80/20), for example, could be applied to select 20% of the SSCs for proactive measures (Electric Power Research Institute, 2008; Norwegian Oil Industry Association, 2008; Pragale *et al.*, 2016). However, this 20% should not include SSCs that are not a priority, but those that pose the greatest risks. The underlying method of prioritization may differ, such as Cause-Consequence Analysis (CCA), checklist analysis, Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Hazard and Operability analysis (HAZOP), Failure Mode and Effects Analysis (FMEA), FMECA and What-if Analysis, presented by Ferreira *et al.* (2020) in the context of material degradation.

The present work proposes a qualitative definition of risk based on probability and consequence severity of obsolescence (Electric Power Research Institute, 2008; Pragale *et al.*, 2016) during life extension.

The probability of obsolescence represents the likelihood that a SSC will become obsolete and present obsolescence related challenges during its extended life (BELSHAW, 2015). Previous authors have proposed different quantitative approaches for estimating the probability of obsolescence, such as using statistical techniques, and machine learning (Trabelsi et.al., 2021; Christina; Olson; Summers, 2021). However, these quantitative approaches rely on a gamut of historical data that is often cumbersome to collect. Furthermore, these approaches are more easily applied to predict types of obsolescence that follow historical trends, such as DMSMS, which might not be the case with new regulations, for instance. Thus, herein the temporal status of obsolescence, as defined in subsection 2.3.1.4 (immediate, short term, long term and negligible) can be used as a proxy for the probability of obsolescence.

The consequence of obsolescence is based on the impact of SSC obsolescence to the overall level of service in three specific dimensions: personal safety, environment, and asset damage. Consequence is also assessed qualitatively (e.g. negligible, marginal, medium, critical and catastrophic).

The combination of probability and consequence in the risk matrix is then used to define classes of risk as Low, Medium, and High (Romero Rojo *et al.*, 2012; Belshaw, 2015; Pragale *et al.*, 2016; Memuletiwon *et al.*, 2017). Operators generally already apply risk matrices in other contexts, such as in the preliminary risk analysis of a unit. The categories used for consequence and risk in other types of risk assessment can be applied directly in the context of obsolescence, as the dimensions of consequence are the same (personal safety, environment, and asset damage).

2.3.1.6 Reevaluate continuously

The non-prioritized items of the obsolescence evaluation must be constantly monitored and revised to mirror changes to SSCs and verify whether the risk associated with any SSC has become a priority during the extended life. In this case, the SSC must undergo a new analysis (Electric Power Research Institute, 2008; Romero Rojo *et al.*, 2012).

Typically, the re-evaluation of excluded items should include, for example: contacting each supplier identified from time to time, systematically evaluating the existence of new standards/regulations and requirements -- especially regarding safety issues (Hokstad *et al.*, 2010) --, identifying the existence of the new technologies available and identifying new operational conditions or new needs in its asset. The frequency for reevaluation cannot be prescribed, as it depends on the results of the risk assessment and the findings of stages 3.1.4 (SSC condition assessment) and 3.1.6 (definition of time-based SSC obsolescence status).

2.3.2 Remaining stages in the life extension management plan impacted by the evaluation of obsolescence

Based on the framework of Ferreira *et al.* (2020), the evaluation of obsolescence affects the definition of LE strategy, assessment of economic issues, and definition of a LE Management Plan and, therefore, must take into account in the output of that analysis. The next subsections, therefore, address the necessary supplements to complete obsolescence management within the life extension management process. After the Obsolescence Management Plan (OMP) is integrated into the LE Management Plan, it must be approved (Memuletiwon *et al.*, 2017) and follow the other stages described in the framework, namely: Obtaining regulatory approval, Implementation of LE Management Plan and Monitoring the LE Management Plan effectiveness. These stages are not in the scope of this article.

2.3.2.1 Definition of the LE strategy from the obsolescence perspective

In defining a life extension strategy for managing obsolescence (Norwegian Oil Industry Association, 2008), not only material degradation (TAN; LU; ZHANG, 2016; Ferreira et. al, 2020), it is important to keep in mind that there are two approaches: reactive and proactive (Konoza *et al.*, 2014; Memuletiwon *et al.*, 2017; Zaabar; Beauregard; Paquet, 2019). The type of approach selected should depend on the risk identified according to the gaps for each SSC.

The proactive strategy (or strategic management), in short, consists of (i) understanding the SSC of the facility; (ii) proactively monitoring information regarding the SSC that is most susceptible to obsolescence; (iii) understanding the current and future possibility of obsolescence of those SSC; (iv) evaluating the gaps expected during life extension; and (v) implementing measures to reduce the possibility of obsolescence and preventing/reducing the effects caused by this component of ageing, such as production interruptions, unforeseen redesign needs, unavailability of the SSCs and increase in associated costs (Akbar *et al.*, 2015; Memuletiwon *et al.*, 2017; Zaabar; Beauregard; Paquet, 2019). Some authors refer to this strategy as a mitigation approach, since the measures taken seek to minimize the impact or the probability of having a problem associated with obsolescence (Belshaw, 2015).

The reactive strategy, in contrast, consists of taking actions as the obsolescence problems occur, that is, as the SSC becomes obsolete (Memuletiwon *et al.*, 2017;. Zaabar; Beauregard; Paquet, 2019; Zaabar *et al.*, 2021). Some authors refer to this strategy as a resolution approach, since the measures taken are aimed at solving existing obsolescence (Belshaw, 2015).

Several authors highlight the need for companies to adopt mainly the proactive approach rather than the reactive one. That is because the cost impact of a reactive approach, such as redesign, is greater than the implementation of proactive strategies (Romero Rojo *et al.*, 2012; Belshaw, 2015; Akbar *et al.*, 2015).

In general, SSCs rated as low risk are managed using a reactive strategy. In this case, the decision is to take effective action only after the problem is established. The proactive strategy, in contrast, is adopted for medium and high-risk components for which an OMP (Obsolescent Management Plan) is developed and implemented to manage risks to make them as low as reasonably practicable (Memuletiwon *et al.*, 2017).

The reactive and proactive types of strategies are further defined by Belshaw (2015) and Memuletiwon *et al.* (2017) for obsolescence caused by DMSMS:

- Reactive strategy – Part search, repair, cannibalization, existing stock, Last Time Buy (LTB), authorized aftermarket sources, gray market, and secondary market, replacement (equivalent), replacement (alternate), emulation, and redesign;
- Proactive strategy – Risk mitigation buy, extended support agreement, planned upgrade, design for obsolescence, and planning.

Other approaches associated with the remaining types of obsolescence can also be mentioned:

- Improved understanding and monitoring of SSC obsolescence problems to guide the adoption of necessary measures (Aealth and Safety Executive, 2012);
- Implementation of different operational and maintenance philosophies (Hokstad *et al.*, 2010) that can allow using the SSCs during the extension of their service life without physical changes to the plant (Lane *et al.*, 2012);
- Adoption of measures to ensure that SSC’s operating condition meets regulation and the new standards (Norwegian Oil Industry Association, 2008), as well as new requirements and needs during the life extension period. Alternatively, the explicit demonstration that failing to comply keeps the SSC's operation at a risk level As Low As Reasonably Practicable (ALARP);
- Application of the management of the change principle, when replacement is necessary but impossible with the same SSC as defined in the original project to ensure that the implications from the operational safety perspective have been properly understood and considered (Lane *et al.*, 2012);
- Incorporation of information related to obsolescence in existing plant processes to facilitate the signaling (flags) of the SSCs already obsolete or in the process of becoming so. The identification allows the people who have access to the SSCs and account for making decisions about it to have a greater awareness of the SSC's situation during their daily activities (Electric Power Research Institute, 2008).

Note that the definition of the strategy in the process of life extension must consider the combined factors of ageing, obsolescence, and material degradation itself, as well as associated organizational issues, which are outside the scope of the present paper.

2.3.2.2 Assessment of economic issues from the obsolescence perspective

The evaluation of the economic viability of the LE plans proposed by (Ferreira *et al.*, 2020) applies an Economic Index (EI) based on the assessment of benefits and costs in the

LE. The evaluation of obsolescence and the definition of the appropriate strategy will, thus, bring other benefits and cost components to the EI.

With regard to benefits, managing obsolescence must lead to an increment in production and improved safety. Therefore, the following improvements should be quantified: (i) reduction of SSCs failure rate; (ii) improvements in SSCs performance, and (iii) reduction of downtime specifically for the SSCs and the plant as a whole. With regards to costs, there will be a capital installation cost and potentially higher operating expenses. Costs should include human resources, e.g. obsolescence managers, and tools (capital resources), e.g. obsolescence monitoring tools. Furthermore, the selection of resources should account for the budget defined for life extension, particularly obsolescence mitigation. Overall, the selection of these resources will influence the calculation of the EI and the planning and expenditures over LE (Romero Rojo *et al.*, 2012).

Alternative to the EI index, other authors proposed economic indices. Liu and Frangopol (2020), for example, suggest the application of a Benefit-Cost Ratio (BCR).

2.3.2.3 Definition of a LE Management Plan from the obsolescence perspective

The formulation of the LE Management Plan, as defined by Ferreira *et al.* (2020), systematizes and documents the actions and strategies established, as well as provides details on the monitoring that must be implemented by operator for life extension. Ferreira *et al.* (2020) list eight topics that must be included in the LE Plan, focusing on the management of material degradation. Albeit quite comprehensive, these topics must be supplemented to incorporate obsolescence issues. Based on a literature review, the present study proposes that each topic of the LE should include the following obsolescence related items:

1) a summary of the technical evaluation of the asset – the main results from Section 2.3.1 of this article, such as a list of priority SSCs and the risk classification (Memuletiwon *et al.*, 2017).

2) overview, premises, and limitations of the decisions – the technical assumptions that defined the priority SSC list, the policy, the objectives, as well as the responsibility for implementing the Plan with the definition of a dedicated professional (called Owner of the Plan). Many authors highlight the importance of this

professional, stating that he/she must be responsible for providing information and requesting feedback from several areas of the company (International Atomic Energy Agency, 2009; Electric Power Research Institute, 2008) and must guarantee the necessary support for implementing and executing the plan (Memuletiwon *et al.*, 2017).

3) statement of the strategy adopted for each SSC analyzed – the obsolescence related ageing issues, and related decisions regarding the resolution or mitigation of the effects of obsolescence for each priority SSC (Memuletiwon *et al.*, 2017).

To manage ageing due to obsolescence, issues more closely related to the operational area should also be anticipated, such as interface points between departments (Lane *et al.*, 2012; Folgerø-Holm, 2014;) and methods for identifying in the plant (flags) the SSC targets of ageing management (Electric Power Research Institute, 2008).

4) relevant inspection, testing, and maintenance program to ensure integrity throughout the SSCs life cycle – the outputs of the evaluation of obsolescence that involve the need to review maintenance strategies and, related, changes to maintenance, test, and inspection plans (Borgonovo; Marseguerra., 2000).

5) specification of the use of indicators during the LE period – a set associated with monitoring ageing due to obsolescence must be taken into account.

6) establish a plan to ensure that the necessary spare parts are available throughout the extended life – if spare parts are associated with the defined strategies, some actions must be directed towards quality control, as well as guaranteed availability.

7) identification of specific procedures to be implemented during LE – procedures that address a systematic evaluation of obsolescence establish how to deal with any identified obsolescence issues and identify continuous improvement in the program (International Atomic Energy Agency, 2009).

8) list of mitigation measures established to reduce risk during technical assessment – short, medium, and long-term actions, estimated completion date, and the party responsible for implementing each of the obsolescence mitigating measures (Memuletiwon *et al.*, 2017).

2.3.3 Case Study Description

The evaluation of obsolescence was never developed by the operators extending offshore production oil and gas facilities, as highlighted by Ferreira *et al.* (2020). This gap shows the importance of developing a framework that can guide obsolescence management. Because no single request submitted to ANP of a facility considering life extension had examples of all types of obsolescence, a hypothetical case study was developed with a combination of information from four real offshore production facilities from three different operating companies. These facilities have different types of installations and are operating in different field conditions (mature fields and post-salt).

For this hypothetical case, we considered that: (i) this is a Floating Production Storage and Offloading (FPSO) unit that has been in operation for 20 years in Brazil; (ii) the operator intends to apply for a 5-year life extension and remain in the same location; (iii) the extension request was sent to the regulatory body one year before the end of the service life of the facility; (iv) the ageing issues associated with material degradation and organizational issues are not relevant and thus only obsolescence issues were evaluated in this article; and (v) the evaluation was restricted to the topside system of the FPSO.

While it would be unlikely for a real offshore production facility to experience all types of issues found in this hypothetical case study, such a broad case study is useful for exemplifying the application of the framework.

2.4 Results

Results from the application of the proposed obsolescence evaluation framework (Figure 2.2 and Table 2.1) to the case study are detailed by stage in Sections 2.4.1 to 2.4.6.

2.4.1 Breaking down the system into manageable portions

The starting point for evaluating obsolescence consisted of the FPSO Equipment list, which presents all the systems of the facility stratified into subsystems and equipment. This list, prepared still in the design phase and revised by the operator throughout the life cycle of the installation, presents useful information for evaluating obsolescence, including location, manufacturer, existence or not of redundancy, type of material, and identification of the change management that gave rise to the modification of the associated SSC. Each of the four types of obsolescence demand different levels of SSC breakdown; in some cases, reaching the component level is necessary.

2.4.2 Development of a database

In addition to the data contained in the FPSO Equipment list, further information was obtained from other lists, such as: pressure relief valve list, blowdown valve list, and shutdown valve list. The last piece of data was obtained from the Computerized Maintenance Management System that established the entire hierarchy of the SSCs of the installation. The pieces of information required for evaluating each obsolescence type are registered in each of the subsections of Section 2.4.3.

2.4.3 Assessment of obsolescence

2.4.3.1 Assessment of availability or support from manufacturers (caused by DMSMS)

Based on an examination of the information on the availability of spare parts and support from the original manufacturers, as well as the expected demand during the intended life extension, four SSCs were found to be impacted in a particularly important manner by this DMSMS obsolescence, as presented next.

1) Pressure Safety Valve (PSV) - PSV valves are safety devices for pressure relief that aim to ensure the safety of people, the environment, and installations in

case of over pressurization of equipment or process systems not controlled by normal means. One year before the intended period of life extension, the following issues were identified: (i) difficulties in the acquisition of a PSV set from manufacturer A (small valves) were expected because the original supplier would leave the Brazilian market, and (ii) supply problems of bellow components for replacement in PSVs from manufacturer B (large valves) were expected due to the end of production by the original manufacturer.

2) Mechanical seals of oil pumps - Mechanical seals in pumps have the function of preventing liquid or gas leakage between the rotating shaft and the fixed pump casing, providing sealing for the set. The original manufacturer of the oil pumps presented the plant operator with a notice of the end of its production in two years. This means that in the next two years, production will be reduced and the operator's remaining stock will not be enough for the entire period of life extension due to the current high failure rates. Failure rates are high for this seal because of the amount of sand in the pumped fluid. Oil pumps have experienced a loss of hydrocarbon containment due to mechanical seal leakage and/or failure due to sand erosion. Sand is abrasive to both the stationary and rotating surfaces of the seal.

3) Heat exchangers - Gas Dewpoint Exchanger – Chiller - A chiller is a heat exchanger located between the two stages of compression of the process gas that aims to reduce the gas temperature and, consequently, remove the water. The manufacturer of this equipment gave notice of the end of production in the next three years. This exchanger is a Plate and Shell Heat Exchangers (PSHE) type and has shown high failure rates in recent years of the unit operation.

4) CO_2 compressor 1st stage discharge Cooler - The exchanger is in the first stage of CO_2 compression, used for injection into the reservoir. The manufacturer of this equipment gave notice of the end of production in the next 4 years. This exchanger is of welded shell and plate type.

Based on the answers to the evaluation questions raised in section 2.3.1.3.1 and a comparison of the period of expected availability of spare parts and support by the original manufacturers and the intended period of life extension, a list of the most impacted SSCs is defined in Table 2.6.

Table 2.6 - List of SSCs impacted by obsolescence in terms of availability or support from manufacturers

SSC	Original manufacturer of the SSC	Location of the SSC	Number of other manufacturers of this SSC	Quantity installed	Time left until discontinuation
PSV (small size)	Manufacturer A	Chemical products injection system	1	10	1 year
Bellow components of PSV (large size)	Manufacturer B	Compression system	15	5	1 year
Mechanical seals of oil pumps	Manufacturer C	Last stage of separation (low pressure)	100	30	2 years
Gas Dewpoint Exchanger – Chiller	Manufacturer D	1st stage of process gas compression	20	2	3 years
CO_2 compressor 1st stage discharge coolers	Manufacturer E	1st stage of CO_2 compression	25	2	4 years

Source: The author, 2024

2.4.3.2 Assessment of the impact of new requirements or demands

A review of the latest revisions of standards, norms, regulations, requirements, and the operator's safety philosophy (both recent and/or expected for the life extension period), highlighted one regulation, in particular, to have a potential impact on certain SSCs, as presented below.

1) Alarms and interlock system in the discharge of Stripping pumps - As a result of accidents, the ANP usually issues a series of recommendations to be met by operators. Therefore, due to the accident that occurred at the FPSO Cidade de São Matheus in 2015, which involved a leak from a stripping pump (Morais et al, 2016 and Ramos; Almeida; Martins, 2020), the ANP issued, among others, recommendation number 31.

- Rec#31: Reciprocating pumps for hydrocarbon transfer must have their discharge protected by interlocking.

In other words, ANP recommendation #31 requires that positive displacement pumps used to transfer hydrocarbons (stripping pumps) shall have the discharge side protected by alarms and an interlock system. The stripping pump is a positive displacement pump, located in the pump room, intended to move hydrocarbon between the cargo tanks.

In the case study system, the Stripping Pumps located in the pump room had not been prepared to implement the recommendation. The pumps did have interlock/trip by High-high pressure on the suction side but did not have interlock/trip on the discharge side.

Therefore, the only SSC that could be impacted during life extension due to new requirements or demands is shown in Table 2.7.

Table 2.7 - List of SSC impacted by obsolescence in terms of new requirements or demands

SSC	Location of the SSC	New requirement or demand	Origin	Impact on the SSC
Alarms and interlock system in the discharge of Stripping pumps	Pump room	Rec#31: Reciprocating pumps for hydrocarbon transfer must have their discharge protected by interlocking.	ANP (recommendations due to incidents)	Non-compliance with a regulatory requirement.

Source: The author, 2024

2.4.3.3 Assessment of the impact of new technologies or techniques

Upon examination of the new technologies or techniques available in the market for SSCs, one of the new solutions was identified as having an impact on a specific SSC, as shown below.

1) Instrumentation interface - The instrumentation interface associated with Gas Turbine Generators is a small, modular Input/Output (I/O) system for distributed applications that performs all of the functions of rack-based I/O. The system contains the following components: (i) adapter – transfers read and write configuration data to and from the I/O module; (ii) terminal base – contains a terminal strip to terminate wiring for two- or three-wire devices, and (iii) I/O module – contains the bus interface and circuitry needed to perform specific functions related to this application. This system is responsible for obtaining instrumentation readings and transferring them to the Programmable Logic Controller (PLC) panel to feed the control system.

Currently, the interface in operation in the facility for the Gas Turbine Generators consists of the 1234-APB and the manufacturer demonstrates that it has a new alternative for this application with a newer and more robust technology, namely: 1234-APB-DPV1. Therefore, the only SSC that could be impacted during life extension due to the availability of new technology is shown in Table 2.8.

Table 2.8 - List of SSCs impacted by obsolescence in terms of new technologies

SSC	Location of the SSC	New technology	Impact on SSC
Instrumentation interface	Next to the PLC associated with Gas Turbine Generators	Newer and more robust instrumentation interface (1234-APBDPV1)	Possibility to increase robustness.

Source: The author, 2024

2.4.3.4 Assessment of the impact of new conditions or needs

Considering the changes in operational conditions – both recent and/or expected for the life extension period –, the increase in the volume of water in the process plant was considered the most relevant issue for the case study facility. The amount of produced water associated with hydrocarbons varies depending on the age of the production wells. This water contains salts, microorganisms, and dissolved gases, in addition to the material in suspension (Triggia *et al.*, 2001). The presence of water associated with oil causes a series of problems in the production phase, including the need for a larger collection, storage, and transfer facilities; failure to meet operational limits of the water treatment system; improper use of cargo tanks for decanting and "complementation" of the treatment of the water produced; reduction of energy efficiency; and operational safety challenges. The latter happens due to corrosion and/or incrustation problems, causing damage to pipes, equipment, and accessories, which can lead to accidents (Xavier *et al.*, 2001).

The increase in the amount of produced water was evidenced throughout the operational life of the asset, particularly in its last years. An intensification is expected in the five years in which the asset will be in life extension. Two main SSCs were identified that will be impacted by the increase in produced water ratio.

1) Hydrocyclones of the Separator - Given this new operational condition, the water treatment system, particularly the hydrocyclones, was found to pose a restriction to operations during the life extension period since they are already very close to their maximum capacity. Hydrocyclones create spiral outflow. The centrifugal force causes the different density phases to separate.

The mounting plate installed in this hydrocyclone already has the maximum number of liners, which is 184. The existing mounting plate cannot handle the installation of more liners, and the water treatment capacity cannot be increased.

2) Production heater - The production heater consists of a shell-tube type exchanger belonging to the trains of the oil treatment system. The purpose of this exchanger is to increase the oil temperature to facilitate the subsequent process of oil separation into its constituent phases, taking place in the Production Separators.

Given the higher produced water ratio, it was identified that during LE more efficient cleaning will be necessary of the exchangers located before the production separators. This is caused by the formation of incrustations inside the hull, making the removal of the bundle of tubes for hydroblasting impossible.

Based on the questions raised in section 2.3.1.3.3 and the discussed gaps, the most impacted SSCs by process changes during LE are listed in Table 2.9.

Table 2.9 - List of SSC impacted by obsolescence in terms of new operational conditions and needs

SSC	Location of the SSC	New operational conditions or needs	Impact on SSC
Hydro cyclone of Separator C	Outlet of Separator C	Greater amount of water	Incompatibility between demand for water treatment and maximum SSC capacity.
Production heaters	Inlet of Production Separators - 2nd stage	Greater amount of water	Greater incrustation and difficulty in cleaning the SSC.

Source: The author, 2024

2.4.4 Identify the SSC condition, SSCs that are barriers to operational safety and categorization according to obsolescence temporal status

Given the four SSC listings established in stage 4.3 according to each type of obsolescence, SSCs were then categorized in three ways:

(i) according to their physical degradation, being identified as green, yellow, and red, as established at the framework defined by Ferreira *et al.* (2020).

(ii) as a barrier, if, in the risk studies on the installation, the SSC were designated as operational safety barriers or whose decrease in reliability and performance would impact the safety of the asset.

(iii) according to temporal terms. Considering the intended period of life extension (5 years), the SSC identified as currently obsolete – those that already are or will be obsolete at the time life extension is approved; projected near-term obsolescence – those that will be obsolete within two years of the approval of life extension; and projected long-term obsolescence – those that will be obsolete after two years of the approval of life extension.

Results are consolidated in Table 2.13.

2.4.5 Definition of priorities

Based on the gaps identified for each type of obsolescence, temporal status established in subsection 2.4.4 was used as a proxy for the probability of obsolescence, according to Table 2.10. In turn, the consequence of obsolescence was qualified according to personal safety, environment, and asset damage, according to consequences severity categories (Table 2.11).

The combination of probability and consequence was used to evaluate risk according to the risk matrix of the operator (Table 2.12), which classifies risks as low, medium, or high. The resulting classification for each SSC led to the priority list, as shown in Table 2.13.

Table 2.10 - Categories of probability of obsolescence for a life extension period of 5 years

Category	Temporal status (t in years)
Immediate	$t = 0$
Short term	$0 < t < 2$
Long term	$2 < t < 5$
Negligible	$t > 5$

Source: The author, 2024

Table 2.11 - Categories of consequence of obsolescence

Categories of consequence	Personal safety	Environment	Asset damage
Catastrophic	- Multiple fatalities inside the facility; - Total or permanent incapacitation of	- Severe damage to sensitive areas or extending to other locations; - Environmental impact that is	- Catastrophic damage to the facility, potentially resulting in well loss.

Categories of consequence	Personal safety	Environment	Asset damage
	multiple individuals.	difficult to reverse even with mitigating actions, with significant magnitude and extent; - Presents a high potential to affect third parties.	
Critical	- Individual fatality inside the facility; - Total or permanent incapacitation.	- High-magnitude impact, reversible with mitigating actions, but restricted to the adjacent areas of the facility	- Severe damage to the facility (long repair time), potentially leading to well loss
Medium	- Severe injuries; - Partial or slow-reversible incapacitation.	- Considerable magnitude impact, reversible with mitigating actions, but restricted to the internal areas of the facility.	- Moderate damage to the facility; - Well loss or damage to well equipment.
Marginal	- Minor injuries to individuals; - Accidents with short-term absence from work.	- Small magnitude impact, confined to the location of occurrence, reversible with mitigating actions..	- Minor damage to equipment or well systems.
Negligible	No injuries or, at most, cases requiring first aid; Accidents without time off work.	- Negligible magnitude impact, confined to the location of occurrence, fully reversible with immediate actions.	Minor damage to the facility without compromising operational continuity; Minor damage to well equipment without compromising operational continuity.

Source: Adapted from operator's existing consequence severity framework

Table 2.12 - Obsolescence risk matrix

	Probability			
Consequence	Negligible	Long term	Short term	Immediate
Catastrophic	**Medium**	**Medium**	**High**	**High**
Critical	**Low**	**Medium**	**Medium**	**High**
Medium	**Low**	**Low**	**Medium**	**Medium**
Marginal	**Low**	**Low**	**Low**	**Medium**
Negligible	**Low**	**Low**	**Low**	**Low**

Source: Adapted from operator's risk matrix

Table 2.13 - SSC priority list and strategy to be adopted

SSC	Type of obsolescence	Identified gaps	SSC condition (*)	Operational safety barriers	Temporal status of obsolescence	Associated risks	Strategy to be adopted
Proactive Strategies							
PSV (small size)	DMSMS	15 units	Green	Yes (high-pressure trip)	Currently obsolete	high obsolescence risk	Adaptation of lines for installing the valve from the new manufacturer. Agreement with a new manufacturer.
Bellow components of PSV (large size)	DMSMS	10 units	Green	Yes (actuators)	Currently obsolete	high obsolescence risk	Keeping a stock of spare parts of bellow components of PSV for the life extension period. Quality control for spare parts.
Alarms and interlock system in the discharge of Stripping pumps	New requirement or demand	Lack of interlock/trip on the discharge side.	---	Yes (high-pressure trip)	Currently obsolete	high obsolescence risk	To install high-pressure trip to pump discharge. Approval of the Classification Society. Modification of the cause and effect matrix of the facility to shut down the pumps in case of high pressure in the discharge.
Hydro cyclone of Separator C	New operational conditions or needs	Lack of capacity of the water treatment system of the facility to accommodate the future water production of 40m3/h.	Green	No	Projected near-term obsolescence	high obsolescence risk	Increase Hydro cyclone of Separator C capacity. Additional liner and new liner plate are provided to increase capacity. This upgrade would increase the water treatment capacity from 373 m3 /h to 420 m3 /h, assuming the operating parameters, such as pressure. Option of upgrading the existing Train C Hydrocyclone V-T2431 is the most practical and cost-efficient. New mounting plate with no compartments/partitions, allowing the installation of 24 additional liners.

SSC	Type of obsolescence	Identified gaps	SSC condition (*)	Operational safety barriers	Temporal status of obsolescence	Associated risks	Strategy to be adopted
Oil pumps mechanical seals	DMSMS	80 units	Red	No	Projected near-term obsolescence	medium obsolescence risk	Installation of cyclone separators to separate sand and other heavier impurities, resulting in a much cleaner fluid that goes through the sealing chamber. The existing discharge piping on crude oil pumps will be dismantled and replaced with new piping and a cyclone separator. Compatibilization of seal stocks, considering smaller failure rates.
Production heater	New operational conditions or needs	Excessive incrustation in the exchanger leads to leakage and loss of efficiency.	Yellow	No	Projected near-term obsolescence	medium obsolescence risk	Need for a new procedure and cleaning of the exchangers (chemical cleaning). The cleaning procedure consists of a batch process (to be performed from time to time). The solution to be used in the cleaning operation consists of a mixture of water and a cleaning product.
Reactive Strategies							
Gas Dewpoint Exchanger – Chiller	DMSMS	1 unit	Red	No	Currently obsolete	low obsolescence risk	Keeping in stock the exchanger needed for the period of life extension.
CO_2 compressor 1st stage discharge coolers	DMSMS	1 unit	Green	No	Projected long-term obsolescence	low obsolescence risk	Keeping in stock the exchanger needed for the period of life extension.
Instrumentation interface	New technologies or techniques	Less robustness of the SSC	Green	No	Projected near-term obsolescence	low obsolescence risk	Maintenance of obsolete technology during life extension.

(*) based on Ferreira *et al.* (2020)

Source: The author, 2024

2.4.6 Reevaluate continuously

During the five years of life extension, the list of priority SSCs should be reviewed to identify possible additional SSCs that may have obsolescence issues. Given the LE period of 5 years, a review frequency of 2 years is proposed. This review shall include verification of (i) notifications from suppliers related to future unavailability of spare parts or services; (ii) new requirements or demands, especially regarding safety issues, (iii) new technologies or techniques available, and (iv) new conditions or needs.

Given this list, a critical analysis must be carried out to verify the pertinence of incorporating other SSCs as a priority, and in the evaluation of the effects of obsolescence during life extension.

2.4.7 Additional stages involved in obsolescence management

2.4.7.1 Definition of LE strategy

Following the risk assessment, LE strategies were selected for each SSC, as shown in Table 2.13. The objective of each of the listed strategies is to decrease the risk level by reducing either the probability or the severity associated with obsolescence.

2.4.7.2 Assessment of economic issues

The collection and analysis of costs and benefits to assess economic impact would require additional data collection, as well as a more extensive and multidisciplinary team. This was beyond the scope and objective of the case study in this article. Therefore, this stage of the proposed framework was not developed.

2.4.7.3 Definition of a LE Management Plan

Given the results of the obsolescence evaluation of the case study facility, and the subsequent analysis stages, the LE management Plan included the following issues:

1) summary of the technical evaluation of the asset - inclusion of the main results obtained in Sections 2.4.3, 2.4.4, and 2.4.5 of the case study.

2) overview, assumptions, and limitations of the decisions - the technical assumptions considered for the definition of the SSC list, as well as the intended objectives, considering each issue identified for the four types of obsolescence, as detailed in Section 2.4.3. This section of the plan also includes the person responsible for managing obsolescence throughout life extension.

3) statement of the strategy adopted for each SSC analyzed – description of the strategy to be adopted for each SSC considered a priority, as presented in Table 2.13.

4) relevant inspection, testing, and maintenance program to ensure integrity throughout the life cycle of the SSC – the strategies associated with obsolescence management, such as quality control of spare parts (e.g. bellows), installation of new lines (e.g. new piping associated with the cyclone separator), inclusion of new instruments (e.g. high-pressure trip to pump discharge) and inclusion of new equipment (e.g. cyclone separators to separate sand) will lead to the need of including new maintenance and asset inspection plans and changes in some of the existing ones.

In addition, the SSCs that have not been replaced and for which reactive strategies will be adopted must be flagged in the computerized maintenance management system.

5) specification of the use of indicators during the LE period – based on the strategies that will be adopted and considering the indicators already identified by Ferreira *et al.* (2020), there should be the monitoring of (i) numbers and types of incidents, (ii) numbers and types of unplanned downtime and production losses, (iii) total maintenance delays, and (iv) unavailability or lack of performance from the main safety systems. Based on these indicators, the need to make adjustments to the Plan should be assessed.

6) plan to ensure that the necessary spare parts are available throughout the LE - considering the defined strategies, adjust the number of spare parts for bellows of

PSV, Gas Dewpoint Exchanger - Chiller, and CO_2 compressor 1st stage discharge coolers to address gaps identified for the LE period.

7) identification of specific procedures to be implemented during LE - this topic was subdivided by procedure type:

(i) Management procedures that describe how systematic assessments of obsolescence and continuous improvement of the program should be performed, as established in Section 2.4.6 of the case study.

(ii) Operating procedures that identify changes to operations of priority SSCs: e.g. cleaning of the exchangers to incorporate the proposed chemical cleaning.

8) list of mitigation measures aimed at reducing risks during the technical assessment. For each strategy identified in Table 2.13, actions, deadlines, and responsible parties were selected.

2.5 Conclusion

The present paper proposes a methodology for assessing and managing the obsolescence of offshore oil and gas production facilities, filling a gap in the literature. Based on a literature review, six stages for obsolescence management are defined: (i) breaking down the systems into manageable portions; (ii) development of a database; (iii) assessment of obsolescence; (iv) identification of the condition of SSCs; identification of SSCs that are also barriers to operational safety; and categorization of SSCs according to the obsolescence temporal status; (v) definition of priorities; and (vi) reevaluating continuously. The proposed obsolescence management process extends upon the framework of Ferreira *et al.* (2020) and adds guidance to the stages of obsolescence evaluation that had not been previously developed. Furthermore, these stages compile lessons learned in obsolescence management from different sectors.

The present study conceptualizes obsolescence as driven by four factors: availability or support from manufacturers, new requirements or demands, new technologies or techniques, and new conditions or needs. Lastly, the paper details the subsequent stages of the life extension planning framework that are affected by the evaluation of obsolescence, namely: definition of the Life Extension (LE) strategy; assessment of economic issues; and definition of the LE Management Plan to guarantee appropriate management of obsolescence.

Because none of the three available cases reviewed by Ferreira *et al.* (2020) had evaluated obsolescence, no single facility had complete information to perform the full obsolescence management process. Thus, to illustrate the application of the proposed framework, a hypothetical system was developed with a combination of information from real offshore production facilities.

The application of the proposed framework to the case study shows that the framework is able to systematically evaluate obsolescence in the context of life extension. The framework simplifies and provides a better foundation for decision-making. Given the range of data collected for the case study, it can be applied as a guide, both by operators – when preparing the life extension plan and presenting it to the regulatory body – and by the regulatory body itself, to support its assessment and recommendations for life extension.

While different assets and asset locations will lead to different results, the proposed stages of the framework can be broadly applied. For different types of assets, the manageable portions and the SSCs involved will differ and assumptions will vary. This will impact the outcome of the evaluation, but the framework stages will remain the same. In the present paper a FPSO was considered, and the analysis focused on the topside of the installation, including SSCs such as: Pressure Safety Valve (PSV) and seals of oil pumps. If, for example, there were a subsea system connected to the facility, other elements would be evaluated as well, such as subsea isolation valve (SSIV), manifolds, and risers. Similarly, if the object of analysis were a rig, other SSCs would be evaluated.

If the asset location were different, the predominant type of obsolescence might differ. For example, if the asset were located in a country with supply chain challenges, obsolescence associated with availability or support from manufactures may be prevalent. On the other hand, if the country is revising environmental and operational safety legislation, then obsolescence associated with new requirements may be more important. And if the asset were on a mature field, where the volume of water is increasing, then obsolescence associated with new conditions may be the most challenging.

Local and company culture can also impact expectations for maintenance, safety and life extension, leading to different assessments of obsolescence. For instance, internal regulations and maintenance policies can influence the condition rating of SSCs and their allowed useful life, as they may be seen as barriers to operational safety. The condition of the field and the characteristics of the surrounding environment will also lead to different evaluations. For example, if an asset were operating in shallow water near environmentally sensitive communities, the severity of the obsolescence consequences would be higher than if the same asset were operating in deep water.

Furthermore, the conceptualization of obsolescence and the obsolescence management process proposed herein are not restricted to the oil and gas industry. While the examples given are for oil and gas, the framework can be generalized to any industry. The framework stages can be applied to any sector since it was conceptualized for assets in general, with lessons learned from various industries. Nevertheless, given its application to the oil and gas industry herein, it is suggested that future studies apply the methodology to other types of assets and industries. Future research should also evaluate the impact of organizational issues. While the evaluation of organizational issues was grouped with the evaluation of obsolescence by Ferreira *et al.* (2020), it requires a different type of analysis, focused on the knowledge of organizational stakeholders, which was outside the scope of the present paper.

3. CHALLENGES IN INTER-ORGANIZATIONAL KNOWLEDGE TRANSFER FOR THE LIFE EXTENSION OF OIL AND GAS FACILITIES

The ageing process of oil and gas facilities poses unique challenges in risk management, especially when operators have the intention to extend their service life. Facility extension has been an object of increased interest in the oil and gas industry because of its benefits. Researchers have identified several organizational issues that can impact this process. Among these, knowledge transfer is a critical aspect in contexts involving facility transfer between companies. The goal of this research is to investigate the inter-organizational knowledge transfer (IKT) elements and mechanisms of oil and gas facilities acquired for life extension and understand their main challenges. A qualitative case study was carried out on the transfer of an oil and gas offshore production facility between companies. The study identified 22 key elements and 27 challenges that the acquiring operating company faced during the IKT process. This case study provides valuable insights that can guide other organizations in similar situations, helping them better manage the IKT process, mitigate potential risks, and ensure smoother operations during and after facility transfer. It can also support the development of future frameworks by managers and oil and gas regulators to evaluate IKT issues as part of oil and gas facility life extension.

3.1 Introduction

The acquisition of oil and gas facilities for life extension has grown in prevalence. Operating these facilities beyond their anticipated duration brings a variety of ageing related challenges. Ageing of an oil and gas facility is multifaceted, it is not simply characterized by the temporal ageing of its equipment (Wintle *et al.*, 2006). According to Ersdal, Sharp and Galbraith (2014), Hornlund *et al.* (2011) and PSA (2005), ageing comprises four categories: functional (physical), technological, knowledge-based and organizational. While most of the literature on the ageing of oil and gas facilities focuses on physical degradation (Hornlund *et al.*, 2011), organizational issues, such as knowledge transfer and personnel ageing, are also crucial (Ferreira *et al.*, 2020).

The evaluation of organizational issues is nevertheless not mandated by global oil and gas regulators for operators to demonstrate that a facility can continue to be safely operated beyond its intended lifespan. For example, life extension cases submitted to the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP), never considered organizational issues (Ferreira *et al.*, 2020). Neither the ANP, the HSE (UK regulator) nor the PSA (Norwegian regulator) have guidelines for evaluating organizational issues (ANP, 2007; HSE, 2014; Norwegian Oil And Gas Association, 2017). The constraints observed in prior regulatory analyses highlight the complexities faced by both operators and regulators in comprehending and evaluating organizational matters.

Based on previous ageing process classifications, potential organizational issues during life extension include ageing of workforce, the need for knowledge transfer and the adaptations arising from changes to company structure, such as company change of ownership, structural organizational changes, mergers, and personnel cuts. Among organizational issues, knowledge transfer is the main challenge in life extension (Ferreira *et al.*, 2023). Within the oil and gas industry, employee retention is a significant issue due to the volatility of oil prices, leading to workforce departures, retirements, or layoffs (Sumbal *et al.*, 2017). Studies in this industry indicate that facilitating internal knowledge transfer can result in cost savings, organizational growth, as well as spur intangible benefits (Aliet *et al.*, 2019).

Because the acquisition of older oil and gas facilities is increasingly common, inter-organizational knowledge transfer is also critical and can introduce further complexities. For oil and gas companies new to a certain basin or country, knowledge transfer between companies is common, as the acquisition of existing facilities may be preferred to grassroot exploration (Brandt; Bates, 2000). Large companies have historically focused on core lucrative areas and have transitioned away from the produce-to-depletion paradigm (i.e., wherein a discovered field is maintained from first production to final cessation). This shift has led to a global acquisition and divestment marketplace (Brandt; Bates, 2000). There is a growing trend of ageing facilities moving from larger to smaller companies, as in the United States and Canada (Brandt; Bates, 2000). While inter-organizational knowledge transfer in these cases is facilitated if employees from the seller company migrate to the buyer company (Martinkenaite, 2012), this is not the norm. In Brazil, for example, since 2019, nineteen offshore units were purchased by smaller companies. None of these included the transfer of technical personnel between companies, highlighting the need for inter-organizational knowledge transfer (ANP, 2010; ANP, 2020; ANP, 2021; ANP, 2022).

Despite the importance of organizational issues in extending the life of oil and gas facilities, and the growing practice of ageing facility acquisition, there is a lack of studies exploring the issues of inter-organizational knowledge transfer in the buyer-seller dyad. For this reason, the present paper focuses on inter-organizational knowledge transfer (IKT) at life extension. The literature on IKT has focused on other types of inter-organizational relationships, such as alliances, company acquisitions, mergers, and supply chain collaborations (Yoo; Lyytinen; Heo, 2007; Martinkenaite, 2011; Milagres; Burcharth, 2019; Whitehead; Zacharia; Prater, 2019). While the aforementioned studies provide the theoretical background for the present paper, as delineated in section 3.2, they do not address the context of the paper, i.e. IKT for facility acquisition.

Given the gaps in the current body of knowledge and practice, the goals of the paper are twofold, to explore the IKT elements and mechanisms of oil and gas facilities acquired for life extension and understand the main associated challenges. The paper addresses two research questions in the context of oil and gas facility acquisition for life extension: *(1) what are the elements of interorganizational knowledge transfer, and the mechanisms associated with them? and (2) what are the challenges related to interorganizational knowledge transfer, and how do they manifest between seller and buyer?* The answers reveal practical implications for oil and gas facility managers and regulators.

The focus of the article is to understand the mechanisms associated with IKT and the respective challenges of this process in the context of acquiring ageing assets in the oil and gas industry by a company that intends to operate them beyond their useful life. To achieve this, a qualitative case study was conducted in which an offshore facility was transferred from one company to another, without the personnel from the original company being transferred to the destination company and aimed to identify the peculiarities of the two environments involved in IKT – the office (onshore) and the facility (offshore). The findings highlight that the various challenges led to a breakdown of knowledge transfer and that several actions can be taken by oil and gas companies to avoid these issues.

3.2 Theoretical Background

Knowledge transfer is the process through which knowledge is transmitted between a source and recipient. This differs from information transfer as it requires understanding, observing, mimicking experimenting, and interlinking information (Oliveira, 2005). It also depends on the experience of the recipient to, for instance, recontextualize the acquired knowledge (Cummings; Teng, 2003) and create new knowledge internally (Giura; Kumar, 2021) through the establishment of new associations (Hou; Li; Lin, 2022). This process occurs in two stages: acquisition and later exploitation of knowledge (Lane; Salk; Lyles, 2001; Martinkenaite, 2011).

IKT occurs beyond the boundaries of the company, between individuals or units of different organizations. This transfer is generally found to be challenging as it involves the multifaceted nature of organizational boundaries, cultures, and processes (Bayer; Maier, 2006). Knowledge from an organization can be highly tacit, specific, and complex which can cause ambiguity and hinder its transfer (Martinkenaite, 2011). Other knowledge transfer issues are related to the loss of knowledge assets, such as by employee turnover, lack of documenting experiences or deletion of documented knowledge, whether unintentional or intentional (Bayer; Maier, 2006). IKT is more effective when these issues are reduced, and ambiguity is addressed through mutual trust and commitment (Becerra; Lunnan; Huemer, 2008). Furthermore, knowledge plays a pivotal role in platform safety, intertwining with all elements of process safety (CCPS, 2007). An effective IKT not only ensures a smooth operational transition but also a safe one. For instance, integrated communication and knowledge of the emergency system can avoid process-related accidents, such as loss of containment (Sani *et al.*, 2021). This section presents the main factors that impact IKT.

3.2.1 Factors that affect knowledge transfer

Previous research has specified several factors that impact IKT according to the type of relationship, as shown in Table 3.1. These factors are considered predictors of the success of the knowledge transfer, i.e., ease, amount, speed, and quality (Lane; Salk; Lyles, 2001). Four types of interorganizational relationships were found in the literature: alliances, company acquisitions, mergers and supply chain collaboration (Schoenberg, 2001; Yoo; Lyytinen; Heo, 2007; Martinkenaite, 2011; Martinkenaite, 2012; Milagres; Burcharth, 2019; Whitehead; Zacharia; Prater, 2019). All these forms of IKT allow companies to access the skills and competencies of their partners, collaborators, or acquired companies, and to develop internal knowledge-based capabilities.

Table 3.1 - Main factors that affect knowledge transfer according to interorganizational relationship

	Alliances	Company acquisitions	Mergers	Supply Chain Collaboration
Interorganizational relationship	Becerra, Lunnan and Huemer (2008); Martinkenaite (2011); Cheung, Myers and Mentzer (2011); Milagres and Burcharth (2019).	Schoenberg (2001); Martinkenaite (2012).	Yoo, Lyytinen and Heo (2007)	Whitehead, Zacharia and Prater, (2019)
Factors that affect knowledge transfer	1) Source and recipient characteristics 2) Knowledge attributes 3) Context of the knowledge transfer 4) Inter-organization dynamics (MARTINKENAITE, 2011; MILAGRES; BURCHARTH, 2019) 5) Individual factors (MILAGRES; BURCHARTH, 2019) 6) Procedural governance (MILAGRES; BURCHARTH, 2019) 7) Relational and Cognitive governance (MILAGRES; BURCHARTH, 2019) 8) Time (MILAGRES; BURCHARTH, 2019)	1) Nature of knowledge 2) Absorptive capacity of the organizations 3) Communication and relationship between organizations (MARTINKENAITE, 2012) 4) Common understanding of the nature of knowledge to be transferred (SCHOENBERG, 2001)	1) Nature of the merger and strategy 2) Nature of knowledge 3) Organizational contexts 4) Time pressure	1) Disseminative capability 2) Partner knowledge 3) Intellectual capital 4) Absorptive capacity of recipient 5) Supply chain collaboration orientation

Source: The author, 2024

None of the forms of interorganizational relationships considered in previous IKT studies describe the context of this article, i.e. facility acquisition and knowledge transfer during a transition phase.

In the case of facility acquisition that does not include company acquisition, the inter-organizational relationship is asymmetric, as the seller may retain relevant information (Flickinger; Klarner, 2016). While there is an asymmetric relationship in supply chain collaborations as well (Awan; Arnaold; GolgecI, 2021), the purchase is of a product or service, not a facility. Furthermore, the supplier and buyer in the supply chain are not competitors. As a result, facility acquisition for life extension likely leads to unique IKT challenges, as follows:

1) facilities are more complex due to ageing and long history of operations (Ferreira *et al*, 2020);

2) facility operations steer away from their optimal point and usually far from the designed specification (Voldsund *et al.*, 2014) and

3) the acquiring company is generally smaller (Barndt; Bates, 2000), and less mature in operational safety risk management.

A framework for evaluating interorganizational knowledge transfer factors in facility acquisition has not yet been established. The present study explores the factors and challenges in IKT during facility acquisition for life extension. The IKT factors of Table 3.1 were used as a starting point, with a focus on factors related to organizational and interorganizational levels. The selected relevant concepts used in this research are summarized and defined in Table 3.2.

Table 3.2 - Definitions of key interorganizational knowledge transfer factors for facility acquisition

Concept	Definition
STRUCTURAL GOVERNANCE	It comprises the characteristics that determine the design of partnerships, i.e. their contractual form and scope. The contract sets the relationship between organizations, their hierarchy for decision-making and the method for conflict resolution, based on lessons learned from previous contracts (Li; Poppo; Zhou, 2010).
RELATED ABSORVITIVE CAPACITY	It is the ability of the recipient organization to value, assimilate, and apply new knowledge in the form being transferred from the source (Lane; Lubatkin, 1998). This ability depends on similarities between organizations with regard to knowledge-processing systems, organizational structure, knowledge base, approaches to problem solving (LAne; Lubatkin, 1998), technologies (Kavusan; Noorderhaven; Duysters 2016), and managerial resources (Schoenberg, 2001).
MOTIVATION	It relates to the behaviour of the organizations and their willingness to provide resources or learn from these resources, depending on their role as source or recipient (Bayer; Maier, 2006).
PRIOR EXPERIENCE	In forming partnerships prior experience allows organizations to collect and structure lessons learned to improve future partnerships across various dimensions (Zollo; Reuer; Singh, 2002; Draulans; De Man, Volberda., 2003; Schilke; Goerzen, 2010; Kavusan; Noorderhaven; Duysters 2016).
TRAINING	It denotes the level of training the source provides to the recipient organization, as to ensure the recipient understands and applies the knowledge (Lane *et al.*, 2001).
MANAGEMENT CAPACITY	It refers to the presence of managerial mechanisms and routines that are designed to store, integrate, and diffuse organizational knowledge (Schilke; Goerzen, 2010). According to Draulans, de Man and Volberda. (2003), three important mechanisms are training, the presence of a manager, and evaluation mechanisms.
INTER-ORGANIZATIONAL ROUTINES	They describe the existence of patterns of coordinated activities and resources among the two organizations that motivate interaction and cooperation (e.g., information gathering, communication, decision making and conflict resolution), refined through repeated collaborations (Zollo; Reuer; Singh, 2002). To manage the assimilation and exploitation of knowledge, organizations may invest in

Concept	Definition
	coordinated activities (Dabic *et al.*, 2020).
OTHER COORDINATION TOOLS	They refer to mechanisms beyond routines, that motivate coordination, such as internal assistance (Ireland; Hitt; Vaidyanath, 2002), integration of systems and databases, roadmapping (Krull; Smith; Husted, 2022), and joint sensemaking (Cheung; Myers; Mentzer, 2011). Joint sensemaking may include information sharing forums, meetings, dialogues and cross-functional teams, board meetings, management meetings, and task-force teams.
TIME	It relates to the amount of time during which the knowledge transfer takes place. Because time compression can restrict knowledge transfer (Escribá-Esteve; Urra-Urbieta, 2002), slow and gradual learning is preferred (Martinkenaite, 2011). The time spent to transfer knowledge does not necessarily represent the knowledge acquired, due to the difficulties and inefficiencies of the learning process (Dyer; Hatch, 2006).
DUE DILIGENCE	It occurs when the buyer evaluates the value and the risks associated with the facility (Brandt; Bates, 2000). It prevents time compression issues (Yoo; Lyytinen; Heo, 2007) and should not be restricted to the standard oil and gas field reserve report (Brandt; Bates, 2000), physical evaluations and financial feasibility, but also include knowledge transfer related factors. Schoenberg (2001) suggests due diligence should have the following objectives: (i) at the macro level, identify areas of potential causal ambiguity and arduous relationships, as well as assess the compatibility of organisational cultures and management styles; and (ii) at the micro level, understand the extent to which knowledge can be codified, identify key individuals that retain knowledge, and map potential arrangements for knowledge exchange interactions.

Source: The author, 2024

3.3 Material And Methods

This research investigates the case of knowledge transfer between seller and buyer for an acquired offshore oil and gas production facility, intended for life extension by the buyer. The case study was carried out at the organizational analysis level, including two different environments (onshore and offshore) with a specific focus on the recipient company. The adoption of qualitative methods in this investigation is predicated on the quest to elucidate a theoretical issue that has yet to be comprehensively understood (Creswell, 2014). This approach is underscored by the literature gap concerning knowledge transfer among firms, especially within the domain of facility life extension.

3.3.1 Research context and case selection

Considering the need to explore in depth a specific context (O'leary, 2005), i.e., IKT in oil platform acquisition for life extension, a case study approach was chosen. An offshore production facility (platform X) which is ageing and whose operation was recently transferred from company A (source) to company B (recipient) was selected. Both companies are Brazilian. Platform X was converted from a vessel into a Floating Production Storage and Offloading (FPSO) unit in 2004. Operations began in 2006, with an expected lifespan of nineteen years. The contract between the two companies was signed in April 2022, and the IKT was executed from July 2022 to January 2023. This is the transition period, understood as the period when both Company A and Company B are offshore. Therefore, during the transition between the two companies, the facility had been in operation for around seventeen years and was nearing the end of its expected lifespan. In this regard, the buyer intended to extend the asset's operational life.

The source company was larger than the recipient company in all respects, i.e. total number of employees, number of platforms operated, as well as oil and gas production. The knowledge transfer took place between the two companies in two distinct environments, offshore and onshore. The organizational structure in the offshore environment remained the same during the transition and afterwards. However, onshore a distinct and exclusive organization for the operation and IKT was established. Onshore, teams were defined according to theme, to facilitate knowledge transfer. These teams were denominated work streams (WS). During the transition, both companies established the roles of transition managers, whose goal was to facilitate an efficient and safe transition of the facility. IKT occurred during two distinct phases in the offshore unit: shadowed operation and assisted operation, as described in Table 3.3. This two-phase approach is recommended by the Brazilian regulator (ANP, 2024) to ensure the acquiring company knows the operational details of the asset and controls risks.

Table 3.3 - Stages of knowledge transfer at the offshore facility

Operation Type	Period		Characteristics	End of stage
	By contract	In practice		
Shadowed Operation	3 months	6 months (Started at Jul/2022)	Plant operation by Company A with observation from Company B.	Until Company B fully takes over the operation (Day 1)

Operation Type	Period		Characteristics	End of stage
	By contract	In practice		
Assisted Operation	Up to 3 months	0-2 months, depending on the offshore function. (Started at Jan/2023)	Plant operation by Company B with assistance from Company A.	Until Company B no longer requests assistance from Company A.

Source: The author, 2024

Staff members from both seller and buyer companies were stationed on the platform for varying periods of time, commonly referred to as "embarking period". The duration was determined according to staff member's role. Notably, some personnel never physically visited the platform during the transition.

3.3.2 Data collection

The study initially aimed to interview a group of professionals from each company. Regrettably, company A did not authorize participation in this research, attributing their declination to unavailability. Consequently, the research's insights were restricted to company B. To address this limitation and mitigate potential bias, the research was modified in three main ways. Firstly, the interview protocol was redesigned to emphasize the knowledge absorption process and the recipient company, which aligns with the primary focus of the literature. Secondly, interviews were conducted at different hierarchical levels of Company B, as to gain a holistic understanding of the IKT mechanisms. Informants were selected from three distinct hierarchical tiers within the company: top management, middle management, and employee level. Thirdly, the analysis was based on the observation of ongoing concrete actions. It relied on secondary data as a complement to primary data, which reinforced statements in the interviews through factual evidence (data triangulation). Examples of secondary data collected include: a document listing the information requested from Company A, a document summarizing lessons learned from previous transition processes by Company B, and presentations made by both companies defining organizational structures during the transition.

Interviews were conducted in February 2023 whereby the recipient company provided insights into the recent IKT process. A semi-structured interview protocol was developed based on the literature, particularly drawing on the review of Milagres and Burcharth (2019).

Open-ended questions were used to stimulate the interviewees to provide details and descriptions (Stewart; Cash Jr, 2015), adequate in the context of qualitative research. The interview protocol was validated in the first interview, conducted with the transition manager, which is why this interview was longer than the subsequent ones. Based on this validation, the protocol was streamlined, certain questions were removed or combined, and adjustments were made to enhance clarity for upcoming interviews. The final interview protocol is provided in Supplementary Material (Table A.1 and A.2).

The number of interviewees was determined to reach a representative group of the company resources involved in the knowledge transfer, as well as the saturation point, where the collection no longer provided further insights into the studied object. To represent the IKT phenomenon during the platform acquisition process, informants from the company's two environments were selected – office (onshore) and facility (offshore).

Interviews were conducted via MicrosoftTeams and recorded, totaling seventeen interviews with an average duration of 1h 44 min, as detailed in Table 3.4. All interviews were video recorded and later transcribed with the use of the software Transkriptor, totalling 806 pages (in Times New Roman font size 12).

Table 3.4 - Characteristics of the interviews

Environment	Hierarchical position of the interviewees (in the transition) [1]	Time per interview	Hierarchical level[2]
Office (Onshore)	Transition Manager	03:08:00	TM
	Coordinator of WS Field Operations	01:14:44	MM
	Coordinator of WS Engineering, Maintenance and Integrity	01:42:31	MM
	Coordinator of WS Naval	01:42:15	MM
	Coordinator of WS HSE (Heath, Safety and Environment)	02:13:00	MM
	Coordinator of WS Drilling and Wells	01:51:22	MM
	Coordinator M&A (Merge and Acquisition)	00:39:52	MM
	Automation engineer	01:02:00	EM
Facility (Offshore)	Offshore Installation Manager	02:22:32	TM
	Offshore Installation Manager	01:56:54	TM
	Production Superintendent	02:10:53	MM
	Marine Superintendent	02:09:43	MM
	Maintenance Superintendent	01:16:05	MM
	Marine Supervisor	01:23:07	EM
	Safety Supervisor	01:05:31	EM
	Mechanical Supervisor	01:29:39	EM
	Electrical technician	02:44:00	EM

[1]One interview session was conducted with each interviewee. [2]TM - top manager; MM - middle manager; EM – employee

Source: The author, 2024

3.3.3 Data analysis

The data analysis was completed in two rounds, using manual coding with Microsoft Excel. In the first round, to identify IKT elements and mechanisms, a content analysis was conducted using data structure methods proposed by Gioia *et al.* (2013), as to delineate the connections between research information and theory. This content analysis applied the following two-step coding protocol:

1) Quotes were deductively assigned to relevant 2nd order constructs, as established by the literature (Table 3.2) (theory centered); and

2) considering that each 2nd order construct was multifaceted, with quotes that spoke to different themes, 1st order constructs were inductively identified (informant centered). Through this inductive process, 22 key IKT elements were identified (Table 3.5), coded as 1st constructs., and aggregated into ten 2nd constructs (Gioia *et al.*, 2013).

In the second round, to identify challenges associated with IKT, a qualitative content analysis - QCA (Schreier, 2014) was conducted on the transcribed interviews. The analysis aimed at describing the content of the communication systematically, and qualitatively. Therefore, before starting the coding, the material was segmented and a coding frame was established in three stages: selection of relevant material, selection of segmentation criterion, and marking of coding units. The transcript from each interview was considered as the analysis unit, and the relevance of quotes was defined based on the presence of statements with a negative connotation. Phrases such as “we were not able to”, “it was impossible”, “we didn’t understand anything” were identified as being related to challenges. Following the thematic criteria, the pre-established topics (1st order constructs) were used as the unit of coding. These constructs were marked throughout the interview material, with simultaneous coding for all units of coding. In this way, for each 1st order construct, key challenging themes were inductively identified and coded as challenges. Since the unit of coding was removed from the analysis context, a general presentation about the transition, provided by Company B, was used as the unit of context (Schreier, 2014).

The 1st and 2nd order constructs identified in the first analysis round answer the first research question, showing the IKT elements of facility acquisition for life extension. The quotes in Table 3.5 provide illustrations into the mechanisms associated with the IKT elements. Although derived from interviews with representatives from both company environments, Table 3.5 focuses on exemplary quotes related to the offshore environment as to enhance reader comprehension. Nonetheless, two 1st order constructs - contractual characteristics and due diligence - exclusively pertain to the onshore environment and thus include quotes from that context.

The challenges derived from the second analysis round answer the second research question. The mechanisms and challenges related to each element are discussed in Section 3.4. As recommended by the author Gioia *et al.* (2013), they are presented as continuous text. For brevity, the analysis of challenges focuses on the offshore environment, as this environment experienced more challenges.

Table 3.5 - Coding overview and illustrative quotes

Illustrative quotes	First-order construct	Second-order construct
(MM) The contract was somewhat standard for Company A with some modifications... Company B requested that the contract have more explicit documentation and the provision of more personnel on board the facility…, but Company A did not accept... regarding knowledge transfer, the contract stated that Company A should provide all information related to safety and those that would guarantee operational continuity, meaning it was very generic.	Contractual characteristics	**STRUCTURAL GOVERNANCE**
(EM) Participation in Company A's meetings was crucial for us to understand what would be done on a daily basis and to follow the activities. However, they didn't want us to participate. After a while, they decided to allow two positions in the meetings.	Decision-making characteristics	
(TM) The general rule for conflict resolution was that "before day 1, decision-making would be company A's responsibility, and after day 1, it would be Company B's." Therefore, a decision-making system was not established in cases of offshore conflicts	Conflict resolution	
(TM) Initially, the transition was supposed to take place in early November, then it was postponed to late November and actually only occurred in January... the relationship between people and knowledge transfer was deteriorating due to the frustrated expectations regarding the transition date.	Transfer period	
(MM) There were things related to knowledge transfer that were fully resolved onshore, but for us offshore, it was not clear... for example, we understood that information was not passed from the Company A offshore team to our offshore team by a decision of Company A... after a long time, we found out that this had been agreed upon with our onshore team... only we did not know.	Alignment of the two companies in all working environments	
(TM) Company B's procedures are more streamlined, so understanding the entire framework of Company A's more detailed procedures (where one led to another) was a bit complicated for the staff…Company B position was broader, so a particular Company A function had to oversee 2 or 3 distinct Company A personnel.	Degree of similarity between the companies	**RELATED ABSORVITIVE CAPACITY**

Illustrative quotes	First-order construct	Second-order construct
(MM) In order to teach us, they needed to have time...and, in my opinion, apart from peak moments of operation, they should have had availability and what was really missing was willingness.	Availability	**MOTIVATION**
(EM) They didn't explain anything proactively...they only answered our questions. The effort and interest were entirely ours. (TM) We would discover something and then go after it to understand it. There was no proactivity from Company A. We discovered several "tricks of the trade" in the plant and started asking questions to understand the way of operating.	Proactivity	
(TM) We asked for the documents to be brought in printed form from shore because we didn't have printers on board... when we arrived at the facility, we didn't have a radio to know where the work was being carried out and direct the team to shadow the activities.	Provision of resources	
(MM) The leadership in other transitions used to say "the company name, overall color and company logo will change, and that's it", and we had no problems or conflicts. So, other transitions were much smoother!	Previous experience	**PRIOR EXPERIENCE**
(TM) We had already learned that knowledge transfer is not possible solely from the delivery of documentation by the selling company, and that they needed to interact with the professionals of the buying company…we have already undergone three very different transitions, and we have not yet taken the time to gather lessons learned on board, what worked and what did not work in these cases, to facilitate future transitions.	Lessons learned	
(MM) We identified the need for training to understand the particularities of: 1) turbines and 2) how to perform maneuvers to return the facility to operation after a blackout (concerning the electrical part). But we didn't understand that Company A could provide these classes.	Identification of training needs	**TRAINING**
(EM) We had doubts regarding the pump system from brand X, because it was different from the ones, we had in other units...but we solved it after the transition when we brought in a specialist from the supplier.	Identification of training needs	**TRAINING**
(EM) A course on the electric panel controller (exclusive to the platform X project) was requested, as it was our first contact with the equipment...the supervisor managed to request a lecture, which was given and helped us better understand it.	Training effectiveness	
(EM) There was guidance given by the transition manager and offshore leadership regarding the objectives of knowledge transfer, what we should focus. (TM) The offshore personnel from Company A seemed to lack information about what needed to be done...the first time I boarded, the facility manager from Company A asked me what I was going to do and if I needed anything from him...so I had to explain.	Transfer objectives	**MANAGEMENT CAPACITY**
(EM) In my view, knowledge transfer would occur by understanding Company A's "how to operate" approach, which requires a good understanding of their procedures, manuals, and observing their	Transfer scope	

Illustrative quotes	First-order construct	Second-order construct
operation itself. (TM) Company A`s personnel had no idea what they could or could not share and would always ask the onshore staff.		
(EM) We reported difficulties with the control room software...we were not familiar with this type of software. However, this demand did not reach the automation personnel onshore, who were the ones who could solve the problem. (TM) I was constantly pushing the onshore personnel regarding the team assembly... But the hiring process was very slow. Additionally, I pushed for documentation, which was not arriving offshore...when the hard drive arrived, what we had requested was not there...very confusing!	Responsibility for the transfer	
(TM) We made reports about the status of the equipment. Every day, I met with the supervisors and/or superintendents and they asked questions to verify my knowledge: "Did you know how to operate equipment X? Did you know its functionality? How to perform isolation?" The supervisors and superintendents always asked if we had assimilated the information.	Evaluation mechanism and method	
(EM) I imagined that Company A would initially think and propose a joint routine with Company B, but this did not happen….so I decided to create my own routine (without asking anyone). I walked around the plant and listened to the radio to find out where the work was being done to keep up with it. (MM) Once we were able to participate in the meetings, this provided greater visibility into what was going to happen on a given day and facilitated the establishment of pairs by discipline.	Definition of routines	**INTER-ORGANIZATIONAL ROUTINES**
(TM) The documentation arrived on board through a hard drive, but this hard drive did not have a clear and objective organization that made sense to the offshore personnel. (MM) When the documentation started coming in printed form, it flowed much better, and we had lost time until then.	Access to databases	**OTHER COORDINATION TOOLS**
(TM) As a means of knowledge transfer, we established two exchange moments - shadow operation and assisted operation. Thus, we closed the pairs between Company A and B to allow the flow of information between the two teams. We also had other forms of exchange, such as moments of function overlap on board. (MM) I was unable to access the cargo material documents (certificates), so the alternative was to access the manufacturer to obtain a second copy.	Mechanisms used for knowledge transfer	
(MM) The shadowing operation is interesting for a maximum of 2-3 months, provided that the team is well-structured and established. However, it is important to understand that each function may require a different amount of time.	Collaboration duration	**TIME**
(TM) The idea behind the due diligence was to assess if the business made commercial sense, while the other issues (degradation of the facility...difficulty or ease of transferring knowledge) would be addressed by the Company B`s team later. In other words, it did not	Due diligence for knowledge transfer	**DUE DILIGENCE**

Illustrative quotes	First-order construct	Second-order construct
provide inputs for the transition phase, nor a prior evaluation.		

Source: The author, 2024

3.4 Results

To answer the second research question, each knowledge transfer element (first order construct) and their related challenges are further discussed in subsections 3.4.1 to 3.4.10. Subsections are numbered according to the second-order constructs defined in the methodology. Notably, the challenges in managing key elements for knowledge transfer displayed significant differences between the two research environments, different from the first and second order constructs. Thus, the discussion of results emphasizes offshore-related challenges, as this environment was more complex and less structured. Consequently, contractual characteristics and due diligence elements are not discussed in subsequent subsections, as offshore personnel do not engage in these matters. In each section, relevant elements are underlined, as defined in Table 3.5, and for each element related key challenges are highlighted in bold and illustrative quotes are in italics.

3.4.1 Structural Governance

Decision-making characteristics. Per the contract signed between the two companies, the responsibility for decision-making in the offshore environment was assigned to Company A during the transition. Company B would become responsible once it assumed the operation (Day 1). This led to one-sided decisions by Company A, who required Company B to seek approval on many day-to-day tasks or even excluded Company B from certain tasks. “We were not able to enter the warehouse. Authorization had to be granted...even after authorization was given, a specific time frame was established for entering and exiting, which made it difficult to carry out necessary tasks there.” (EM)

Some of Company A's **unilateral decision-making, contrary to the effectiveness of knowledge transfer**, made the transition more difficult, bureaucratic, formal, and time-consuming. Gradually, Company A relaxed some of these constraints due to Company B's persistence. Confronted with several limitations, such as not being allowed to participate in Company A's meetings, Company B explored alternatives to become more aware of what was being done at platform X, such as by tuning into planning meetings via radio. However, this proved to be both time-consuming and an inadequate solution for accessing the required knowledge.

Conflict resolution. Throughout the transfer, discrepancies between the companies arose and were resolved on a case-by-case basis, as evidenced by their approach to handling COVID cases: "Regarding the reporting procedure for COVID cases and incidents involving Company B's personnel, what should be done? There was no previous structured process on how to handle these cases, so we had to figure out what to do when the situation arose" (TM)

This **ad-hoc approach to conflict resolution during knowledge transfer** caused a waste of time.

Transfer period. The contractually set date for the facility transfer was postponed several times. Initially scheduled for the beginning of November 2022, it was later rescheduled to the end of November and eventually occurred in early January 2023. The **unpredictability of the knowledge transfer period,** i.e., date extensions and prolonged shadowing operation (from 3 to 6 months), led to frustration among Company A teams, making the knowledge transfer process offshore difficult, as pointed out by TM: "The frustrated expectations hindered the course of knowledge transfer, so the additional 3 months we had could not be fully utilized due to the decline in the partnership."

Alignment of the two companies in all working environments. Certain IKT procedure definitions and approaches, agreed upon by the two companies in the onshore environment, were not reflected in the offshore environment. For instance, procedures for information sharing by Company A and the role of suppliers offshore were not aligned between environments:

> We would embark the suppliers to survey critical equipment and understand the real situation of the plant... they needed to open the equipment, but Company A only allowed them to do a visual evaluation, not accessing the equipment completely. We brought this issue to the onshore management who gave us feedback that indeed the

> suppliers couldn't't really access the equipment, it was only for a visual assessment...this was not clear to us...we didn't understand anything! (MM)

While some decisions, such as centralized documentation availability, were consensual between the two companies in the onshore environment, the offshore personnel believed they were unilateral. This **lack of transparency regarding consensual decisions made in different environments** left offshore personnel without clear guidance and resulted in wastage of time in attempting to reverse previously agreed-upon situations.

3.4.2 Related Absorptive Capacity

Degree of similarity between companies. Many aspects were pointed out by the interviewees as different between the two companies:

1) operating approach (more bureaucratic versus more flexible): "The control room operation was remote, very different from what the Company B's personnel were used to, making it difficult for them to understand the operation." (TM);

2) job description (specialist versus generalist): "Company A had a greater segmentation regarding the duties of its professionals than Company B…so, it was more difficult to match the assignments of Company A versus Company B." (TM);

3) boarding schedules (shorter vs longer): "The boarding scales of Company A and Company B did not match; we would start by learning from one person and then another would come." (EM);

4) operational procedures (more detailed with referencing between procedures versus more concise):

> Company B's procedures were more detailed, containing everything needed in a single document. Company A's procedures referred to several other procedures that needed to be read to understand the whole... we were not used to it... so, reading them alone, I felt difficulty... (TM);

5) organizational structure (lean versus with more hierarchical levels) and involvement of onshore personnel in offshore decision-making (more independent versus less independent):

> The personnel in charge of large machines (compressors and turbines) at Company A, who were on board, were completely separated from the on-board maintenance

> personnel and were managed from the shore. This structure was totally different from what we had at Company B. (EM);

6) autonomy of offshore personnel (low vs moderate): "…the lack of autonomy of the offshore personnel was strange to us... they would ask the ground staff if they could do anything." (EM);

7) scope of work (more limited or more comprehensive*).*

> In situations such as plant restart after a blackout, we had difficulties because Company A's professionals operated the electrical part of the control room, but Company B's operators did not operate that part in other facility... so we needed to learn everything from scratch! (EM).

Taking job description as an example, some positions in Company B were found to be more generalists than those in Company A. Consequently, the responsibilities of a Company B professional were often an accumulation of several Company A professionals' duties (who were more specialized). This made it difficult to connect professionals from both companies and define pairs for observation activities, leaving Company B employees somewhat confused about which professionals they should accompany and observe. Although differences were identified, Company B was **unable to accommodate differences**. No mitigating strategies were adopted to minimize the negative impact of differences on the knowledge transfer process.

3.4.3 Motivation

Availability. Offshore professionals from Company B were fully available for knowledge transfer, being onboard the platform for that sole purpose. However, they perceived that offshore professionals from Company A, in general, lacked availability due to operational tasks: "In five opportunities in the platform, for example, our Superintendent could only go to the plant with his Company A`s counterpart twice...his counterpart claimed to have no time, being overwhelmed with work...having many tasks to handle." (MM); "They had available time, but Company B was not a priority. The priority was to operate." (MM)

Therefore, there was **competition between operational functions and those related to knowledge transfer**, and **low priority given to scheduling of knowledge transfer**.

Proactivity. Company B exhibited significant proactivity in their relationship with Company A, as shown in their approach of "investigating" the platform: "We found out that there is a "project error" in equipment X... I only got the explanation because when walking through the plant I noticed it was taller than what I was used to seeing in other units and decided to ask...I did almost investigative work…." (EM)

Contrariwise, interviewees perceived Company A not to be proactive. Company A professionals believed their responsibility during the transition was limited to operating and answering questions, without proactive preparation or addressing of important topics: "They weren't concerned about my learning...they were there working, operating...if we wanted to, we could follow along..." (EM)

Thus, there was an **unstructured knowledge transfer, reliant on questions,** and a **misunderstanding of shared knowledge transfer responsibility**.

Furthermore, Company A personnel who were uncertain of their field assignment location after the transition, showed an **unwillingness to share knowledge due to resistance to acquisition**.

> To clarify doubts, some Company A's professionals would detail the issue, others would ask to direct the question to another team or person. I felt that Company A's personnel, who had already known where they will go after leaving the facility, were more open and shared more information. (EM)
>
> … people did not accept the facility transition, so there was a lot of resistance in transferring knowledge. (MM)

These challenges made the acquisition process more difficult, expensive, and less efficient. As a result, matters that should have been addressed during the shadowed operation phase emerged as surprises during Company B's operational phase.

Provision of resources. Initially, Company B did not provide all the necessary resources to facilitate knowledge transfer, such as radio, computer, printer, necessary documentation, and server with organized information for offshore personnel:

> From the operational personnel in my team, I demanded the reading of Company A's manuals and procedures... but we couldn't enforce this reading through the system because our offshore network was not yet provided by onshore team, and additionally not everyone had a computer to access the documents. (TM)
>
> ...at the beginning, it was only one hard drive for everyone to consult, so we often had to keep passing the hard drive "back and forth. (EM)

Offshore teams began to be defined in late July 2022, together with shadowed operations, but were only fully established in January 2023, right before the start of assisted operations.:

> We were there to acquire knowledge, but we did not have a formed team. We needed the onshore team to hire personnel to work offshore as soon as possible so that they could get to know the installation and learn from Company A in the time we had. Without people, how can knowledge transfer be accomplished? (MM)

The **lack of resources prior to beginning knowledge transfer** hindered the monitoring of offshore activities, making the knowledge transfer process slow and difficult.

3.4.4 Prior Experience

Previous experiences. Some offshore leaders and employees from Company B had prior experience in IKT during facility transitions in the role of recipient company, as described by TM: "As the intended transition time was short, we used our most experienced resources from the fleet". Nevertheless, all interviewees noted that this transition was different from previous cases, in which IKT was facilitated by the migration of people from the source company to the recipient. Engaging with the previous source companies to gain knowledge about the facility posed no challenges.

While Company A also had experience as the source company in other facility transitions, the professionals who led and were involved in this offshore transfer had no experience. Only Company A's onshore personnel were experienced, showing a **limited experience in facility transition** of operational personnel, as pointed out by TM: Nobody on board of Company A had experience in facility transition. Only on the last day of the transition, Company A called two people who had gone through transitions (with another company) to help in the process.

Lack of prior understanding of the differences between previous and current transitions led to a failure to anticipate difficulties. For example, Company B was unaware that the offshore structure of Company A had particularities, different from previous experiences. Therefore, there were difficulties in replicating the model that had already been learned and systematized in other transitions, as highlighted by TM: "To the extent that we could, we used the same mechanisms that we already had experience and that had worked in the other transitions. But, sometimes, because of the differences imposed by Company A, it didn't work.".

Moreover, the Company A offshore personnel's lack of experience hindered their understanding of the objectives, scope, level of collaboration, and the requirements for a successful of IKT.

Lessons learned. Company B leveraged insights from previous experiences to contribute to knowledge transfer. Examples of formal and informal insights included: (i) the implementation and planning of shadowed operation and assisted operation; (ii) an understanding that knowledge transfer requires more than the delivery of documentation by the source company; (iii) the implementation of management and operational tools, and (iv) an approach for acquiring knowledge through reading manuals, technical drawings, and field verification. "The stipulated time of 3 months for the transition considered the times we had practiced in previous transitions, for example". (TM); "We brought to this transition, for example, the way of acquiring knowledge that had already worked in previous transitions (reading manuals, technical drawings, field verification, line run for understanding the operation)". (TM)

Offshore lessons learned had not been formally recorded, unlike onshore. The Managed Transition of Operated Assets document which summarized lessons learned by Company B only included onshore lessons. This **lack of documented lessons learned** negatively impacted the IKT process, making it difficult to standardize how offshore personnel would acquire knowledge. Consequently, Company B delegated to each employee the responsibility for defining their knowledge transfer approach, a task that hardly matched their operational role. The onus was placed on operational personnel to specify vital IKT aspects, including the selection of tools for the acquisition and assimilation of knowledge.

3.4.5 Training

Identification of training needs. Most of the time, Company B did not identify the need for training by Company A or did not even understand that it could request it: "If

Company A could have provided small courses about systems or procedures, it would have been much better for us to learn and faster. They could have gone system by system, explaining the parameters, showing the plant and supervisory…showing everything in detail." (EM)

Lack of understanding that training from the source company is a means of acquiring knowledge from a partner company led Company B to seek more costly solutions, such as external training or assistance from equipment and systems suppliers.

Training effectiveness. When requested, training was provided by Company A based on personnel availability. Training facilitated the assimilation of knowledge, as relayed by TM: "Trainings were requested and promptly made available by Company A for issues that were different from our units (plant operation procedure for gas compression, power generation, water injection, water treatment)". No specific challenges were identified in this regard.

3.4.6 Management Capacity

Transfer objectives. The transition manager and offshore leaders initially communicated knowledge transfer objectives to Company B's offshore personnel. However, interviewees reported that these directions were not effectively communicated internally to Company A's offshore personnel. Apparently, some of the information about the transfer was only conveyed to Company A offshore personnel by Company B personnel: "Company As staff gradually understood the purpose of our presence on board throughout the process. Initially, they were not aware of it, but as we brought our team on board, they understood that the transition and knowledge transfer needed to take place." (MM)

The **unclear definition of objectives** contributed to inefficiency and wasted time.

Transfer scope. Although objectives were initially established, Company B's offshore personnel did not have a clear understanding of the work scope during the transfer. Various conflicting scope definitions were specified by the interviewees, including:

(i) understanding Company A’s operating approach: “We received all procedures, all necessary documents…so we had to read them all, but the most exhausting and difficult part was to seek tacit knowledge.” (TM)

(ii) getting familiarized with the platform, but not becoming acquainted with Company A’s procedures: “To fulfill the guidelines given by the leadership, I needed to familiarize myself with the platform... but there was no need to read Company A’s procedure because Company B would operate differently.” (EM);

(iii) diagnosing the platform and its equipment to provide input to management: “I understood that I needed to diagnose the condition of the platform (equipment health) to feed the managers.” (EM); and

(iv) checking if Company A procedures needed any updates to fit Company B’s way of operating: “I needed to verify if Company A’s procedures needed any updates to fit Company B’s way of operating.” (EM)

The different scopes illustrate an **unclear prioritization between tacit knowledge acquisition and physical asset assessment** by offshore employees. Company A’s personnel lacked clarity about the scope, resulting in hesitation to share certain information as highlighted by TM: “One time my counterpart said, ‘I don’t know if I can give you this information, as a person and a professional, I don’t see any problem, but I don’t know if I'm authorized to share it*”*. This led to inefficiencies and time-consuming authorization processes for sharing knowledge.

Responsibility for the transfer. There was no clear coordination for knowledge transfer between offshore and onshore leadership. Thus, Company B did not have a holistic view of the IKT process: “As there was no one responsible for both onshore and offshore coordination, when the onshore personnel needed to resolve issues from other facility, the offshore personnel felt lost... it was very difficult, we were left without support.” (MM)

Offshore personnel had to rely on onshore personnel for support, whose responsibilities made them unable to always provide the necessary assistance. This caused a **poor interface between offshore and onshore team**, with ineffective and time-consuming support. Offshore personnel frequently made requests to onshore personnel, yet there was no systematic approach to address them. These requests were made in meetings, by emails, or through feedback reports. As a result, some of the tools and materials prepared onshore did not meet the expectations of the offshore teams or were simply not provided to them:

"Regarding the lifting equipment certificate information, I even asked the onshore team to request it from Company A, but I did not receive a response." (MM)

The **lack of dedicated personnel to focus on and coordinate knowledge transfer** also prevented the identification of possible synergies between environments.

Evaluation mechanism and method. The offshore personnel used formal mechanisms such as meetings, weekly reports, and reports at the end of the embarking period to monitor the knowledge transfer that occurred offshore. However, the content of this feedback mainly focused on: operational and communication difficulties, rather than tacit knowledge of the platform ("how to" and "tips and tricks"), as highlighted by EM: "The reports were about operational difficulties...Daily reports to the supervisor aimed to highlight the difficulties in obtaining a document… equipment that was not operating correctly.".

While Company B had formal management systems in place to evaluate employees in specific competencies of day-to-day operations, these were not applied in the transfer. Instead, the offshore leadership used informal mechanisms: "To verify the learning, an oral test was applied by the leadership. I asked them to explain to me what they had learned, for example, a question I would ask was "if you had to return to the facility from a black out, how would do you do it?"

This **lack of systematic definition of evaluation tools** offshore added complexity to the work of the offshore leadership. They lacked a structure to verify employe learning, making it difficult to guarantee that the necessary knowledge had been accessed and assimilated.

3.4.7 Inter-organizational Routines

Definition of Routines. Initially, no formal routines were established between the two companies for knowledge transfer. After Company A's authorization, Company B began partaking in daily planning meetings. Although not established for knowledge transfer, these meetings were essential for understanding the activities to be monitored by Company B's offshore personnel. Apart from attending these meetings, no other routines were established between the companies. Company B’s offshore personnel created informal routines for acquiring knowledge, such as (i) reading technical documents, (ii) familiarizing themselves with the platform, (iii) identifying platform idiosyncrasies, (iv) monitoring work, and (v) raising questions. “My routine was to attend the morning meetings... questions were randomly answered during coffee breaks, for example.” (EM)

These routines were unaligned with Company A and were not standardized, as **individual routines were set according to availability and not for optimal knowledge transfer.** The interviews clearly showed that **independent routines were set for each company’s operational teams:** “Each operator had their own routine. I structured it this way... Each one created a method to study and establish a routine.” (EM)

Establishing ad-hoc routines engendered several issues, including:

1) difficulty in establishing an effective knowledge transfer dynamic between counterparts, as Company A employees had to operate and maintain the platform while providing explanations and answering questions: “The transfer relied heavily on the outsourced staff, who were more accessible than the Company A’s own personnel.” (MM)

2) more rework for Company B professionals as they had to replan their daily work based on new activities communicated under short notice: “I would plan my day, but if I heard on the radio that some work was going to be done, I would interrupt what I had planned and go to the plant to accompany the service.” (EM)

3) increased dependence on the Company A counterpart, which could result in an unfeasible system if the person was not receptive or available. “As it depended on the counterpart, to have a good knowledge transfer, there were some professionals who did not have the chance to have ‘the best teacher’”. (EM); “If I hadn't boarded with the "the best teacher", I followed my established routine alone... mapping and diagnosing the equipment.” (EM)

Offshore leadership believed routines should involve both theoretical and practical components, but this was not fully adopted by team members. Routines for acquiring knowledge in specific situations, such as unexpected shutdowns, would have contributed to the learning process.

3.4.8 Other coordination tools

Access to databases. Company B's access to Company A's database was managed by Company B's onshore personnel. They aimed to centralize the information provided by Company A by sending hard drives with the documentation to the offshore team. The offshore leadership was responsible for filtering and organizing the material. However, the hard drive approach was not user-friendly, as documents were difficult to locate, content was misaligned, there weren't enough computers to access the data, information was provided in batches. Moreover, there were delays between request and delivery: "It was impossible to navigate through the documents in the hard drive without a good description and search tool. Thus, it became impossible to find anything or it would take hours to find a manual." (EM)

The offshore leadership struggled to classify, prioritize, and organize the hard drive contents, since the **documents were not organized prior for knowledge transfer**. Offshore personnel felt discouraged by the slow and difficult access to information. "Every time I needed a document, I had to go through my supervisor, who would then go to the Superintendent, who would contact Company B's onshore personnel to request the documentation to Company A. Then, it would come offshore through the hard drive." (EM)

There was a **piece-meal sharing of documents, not based on type of function and system**. Some essential information was not provided through software or server access (as requested by Company B), was not delivered in print (as requested by Company B), or never arrived (requiring full data collection or consultation with the manufacturer). The goal of avoiding access to outdated documents by centralizing documentation was also not achieved because Company B offshore personnel accessed existing documents, such as old printouts, on site.

Mechanisms used for knowledge transfer. The IKT offshore generally relied on the following mechanisms: (i) individual prior reading; (ii) dialogue between counterparts; and (iii) platform visits for evaluation and familiarization. Alternative methods included: (i) consulting equipment and systems suppliers; (ii) overlapping of operators with the same function to enable knowledge exchange on board among Company B's professionals; and (iii) hiring third-party contractors who were already operating the facility.

There was a **lack of alignment between mechanisms applied, knowledge type, and preferred learning style**. For some, merely observing was a barrier to learning, as offshore personnel were found to generally prefer hands-on experiences. The lack of active involvement in operations posed challenges in acquiring and assimilating knowledge: “The shadowing period was very extensive because I couldn't learn just by observing...I preferred an assisted operation from the beginning...I was a bit lost as an observer, without operating.” (EM); “The shadowing period was very long...just looking doesn't work. Shadowing without training, without explanation, without delving into the problems, doesn't work...” (EM)

Staff overlapping was used by Company B to allow staff with the same function to spend time together offshore. While this overlapping yielded good results for internal knowledge transfer, it was unplanned and could have been better utilized. Furthermore, seeking suppliers as alternative knowledge sources added little value because they were only able to perform a visual assessment. This turned out to be more costly than acquiring knowledge directly from Company A.

3.4.9 Time

Set Collaboration Duration. The duration of the IKT was found to be highly dependent on other features, e.g. documentation and team availability, as well as how early certain features were established, e.g. counterpart pairing and offshore routines. When operators arrived at the platform for knowledge transfer, they did not have access to all the necessary documentation before starting to monitor offshore activities. Time spent on the platform was used to define counterparts between Company A and Company B and to define the routines of each pair of counterparts. Furthermore, time spent on the platform was not consistent. The offshore leadership stayed for 6 months, in total, on the platform. Some functions stayed for 3 months, and others for no time at all.

Limited time on board was spent carrying out the knowledge transfer itself due to the **lack of a detailed plan to accurately estimate time required**. The efficacy of knowledge transfer would have been significantly enhanced had there been a proactive identification of essential documents, their precise locations, delineation of roles between Company A and B, and the establishment of offshore protocols prior to the deployment of Company B’s personnel offshore: "When you have a well-structured and agreed-upon plan between the companies, where there is alignment between offshore and onshore teams of both companies, 90 days is sufficient with all the necessary resources available…" (TM); "If I had stayed longer, I would have understood which modules were more sensitive, which points caused problems, but with only few embarks I didn't have enough time to do so." (EM)

In light of the findings delineated in the preceding subsections, Table 3.6 offers a comprehensive summary of challenges categorized by IKT element.

Table 3.6 - Consolidated challenges

IKT elements	Challenges
Contractual characteristics	(NA)
Decision-making characteristics	Unilateral decision-making contrary to the effectiveness of knowledge transfer.
Conflict resolution	Ad-hoc approach to conflict resolution during knowledge transfer.
Transfer period	Unpredictability of the knowledge transfer period.
Alignment of the two companies in all working environments	Lack of transparency on consensual decisions made in different environments.
Degree of similarity between the companies	Unable to resolve differences.
Availability	Competition between operational functions and those related to knowledge transfer. Low priority given to scheduling of knowledge transfer.
Proactivity	Unstructured knowledge transfer, reliant on questions.
	Misunderstanding of shared knowledge transfer responsibility among companies.
	Unwillingness to share knowledge due to resistance to acquisition.
Provision of resources	Lack of resources (software, hardware, equipment & personnel) prior to beginning knowledge transfer.
Previous experiences	Limited experience in facility transition.
	Lack of prior understanding of the differences between previous and current transitions.
Lessons learned	Lack of documented lessons learned.
Identification of training needs	Lack of understanding that training from the source company is a means of acquiring knowledge
Training effectiveness	---
Transfer objectives	Unclear definition of objectives.
Transfer scope	Inconsistent scope definition.
	Unclear prioritization between tacit knowledge acquisition and physical asset assessment.

IKT elements	Challenges
Responsibility for the transfer	Lack of dedicated personnel to focus on and coordinate knowledge transfer (covering offshore and onshore enviroment).
	Poor interface between offshore and onshore team.
Evaluation mechanism and method	Lack of systematic definition of evaluation tools.
Definition of routines	Independent routines set for each company's operational teams
	Individual routines set according to availability and not for optimal knowledge transfer.
Access to databases	Piece-meal sharing of documents, not based on type of function and system.
	Documents not organized prior for knowledge transfer.
Mechanisms used for knowledge transfer	Lack of alignment between mechanisms applied, knowledge type, and preferred learning style.
Time	Lack of detailed plan to accurately estimate time required.

Source: The author, 2024

These identified challenges underscore a failure in knowledge transfer between the two companies. "The documentation is still a problem to this day. We are operating the facility and I still need documents that I can't find. Until February [with the operation under Company B], they were still separating and organizing the necessary documentation for the team." (MM)

This failure led to a knowledge gap for Company B, evidenced by learnings which only occurred after the knowledge transfer phase was completed: "We discovered several "surprises" after day 1, for example, that there was a compressor that we could not operate at all in automatic mode, which was totally different from what we were used to... that there was a serious capacity limitation problem unit loading, that we needed to take actions..." (MM)

3.5 Discussion

Given the gamut of challenges explored in the results, several actions can be taken by oil and gas companies to avoid IKT issues during the acquisition of offshore platforms for life extension. For each challenge, potential solutions are identified below. For example, for the challenge related to an ad-hoc approach to conflict resolution, the recommended solution involves to plan and mandate a conflict resolution procedure.

Guidelines for improving IKT are suggested based on the stage of knowledge transfer, when they would be applied, namely: pre-transition, transition, and post-transition. The transition is understood as the period when both Company A and Company B are offshore. Most of the challenges identified stemmed from failures in planning. Thus, most of the guidelines are relevant to the pre-transition phase. Given the rarity of facility acquisitions for companies, coupled with the fact that knowledge transfer deviates from regular operational tasks, it becomes evident that meticulous planning is essential for its execution.

Pre-transition - In this phase, it is important that onshore and offshore teams of both companies are aligned. Leaders and key team members from both companies should: (i) jointly define a detailed knowledge transfer plan; (ii) select staff who have previously been involved in transitions; (iii) ensure that employees are available for knowledge transfer during the transition period (this may involve providing opportunities for knowledge to be transmitted at a separate time from when the employee is not operating the platform); (iv) ensure that employees are aware of the knowledge transfer plan and their roles; and (v) ensure data resources are organized and made available prior to the knowledge transfer.

The detailed knowledge transfer plan should consider the: (i) objectives and scope of knowledge transfer; (ii) level of collaboration between teams; (iii) participating teams and key positions; (iv) pairs of professionals from the recipient and source companies; (v) time required for transfer, in the office and offshore for each identified pair of professionals (keeping in mind space constraints offshore); (vi) materials to be transferred; (vii) a combination and prioritization of mechanisms to be adopted (e.g. training, operational observation, simulated operation, pre-reading of procedures, directed study, consultancy, task forces, job overlap, roadmapping, among others); (viii) inter-organizational routines associated with each identified pair of professionals (including day-to-day facility operations and specific events such as recovery from a blackout); (ix) methods of provision and receipt of documentation; (x) prerequisites for accessing the offshore facility; (xi) method of monitoring actions and activities to ensure alignment with the defined objectives, scope, and level of collaboration; (xii) content, format, and frequency of feedback from respective pairs regarding the progress of knowledge transfer to leadership; (xiii) conflict resolution procedures; (xiv) potential safety issues and mitigating strategies; (xv) comparison of organizational structures, procedures, systems and software, and strategies for addressing differences.

It is also very useful for the recipient company to designate a person or team responsible for the success of the knowledge transfer. This designation should be communicated to all levels of the organization. The designated individual/team would be responsible for: (i) defining the coordination method and proposing interfaces between environments to ensure alignment and smooth information flow; (ii) establishing a knowledge transfer monitoring system; (iii) organizing the material received from the source company; and (iv) providing the necessary documentation for each pair in an organized manner based on the specific needs of each pair.

Transition - During the transition phase, leadership at different levels within the companies should: (i) Communicate objectives, scope, and collaboration level clearly to their teams; (ii) Regularly evaluate effectiveness of actions, routines, mechanisms against objectives; (iii) Balance tacit and operational knowledge acquisition; (iv) Standardize actions across professionals where possible; (v) Adopt additional measures (training, job overlaps, directed study) for complex or differing areas; (vi) Ensure adequate knowledge exchange time is being allowed; (vii) Record lessons learned throughout the transition; (viii) Collect feedback throughout the transition to identify best practices and ineffective strategies; and (ix) Address challenges as they come up if possible.

Post-Transition - In the post-transition phase, leadership and key team members from both companies should: (i) Compile recorded lessons learned and codify them; (ii) Collect final feedback and compile all feedback collected to identify best practices and ineffective strategies; and (iii) Establish a systematic approach for recurring codification of lessons learned.

3.6 Conclusion

This paper elucidates the main elements an organization needs to manage during IKT within the context of oil and gas facility acquisition for life extension. Drawing on the case study of an ageing platform X transferred between two companies of differing sizes, 22 key elements are identified that need to be managed during IKT. These elements may contribute to a larger Life Extension Management Plan to be submitted to the regulatory agency, as defined by Ferreira *et al.*(2020). These include: contractual characteristics, decision-making characteristics, conflict resolution, transfer period, alignment of the two companies in onshore and offshore environments, degree of similarity between the companies, availability, proactivity, provision of resources, previous experiences, lessons learned, identification of training needs, training effectiveness, transfer objectives, transfer scope, responsibility for the transfer, evaluation mechanism and method, definition of routines, access to databases, mechanisms used for knowledge transfer, collaboration duration and due diligence for knowledge transfer. These elements unfold into 27 challenges faced by the operator. The findings highlight that the various challenges led to a breakdown in knowledge transfer.

This research contributes to the body of knowledge by addressing two key gaps in the literature, (1) the lack of studies on organizational issues for oil and gas facility life extension; (2) the lack of research on knowledge transfer in the context of facility acquisition. The paper addresses the first gap by underscoring the importance of organizational issues as part of offshore facility life extension. It delves deeper on knowledge transfer, an essential aspect of organizational issues, concentrating specifically on its nuances during the operation transition of aging facilities. By providing details on the relevant knowledge transfer challenges, it unpacks organizational issues flagged by previous authors (Hornlund *et al.*, 2011; Ersdal; Sharp; Galbraith, 2014; Ferreira *et al.*, 2020; Ferreira *et al.*, 2023). Contrary to previous literature which treats each organization, either source or recipient, as a monolithic entity, this study showcases the challenges within separate environments (onshore and offshore) of the same organization.

To address the second theoretical gap, the paper contributes to existing research by adding the mechanisms behind the IKT elements of an aging facility acquisition. The identified elements provide novel theoretical insights specific to facility acquisition, which differ from previous studies focused on company acquisitions, mergers, and partnerships (Yoo; Bayer; Maier, 2006; Lyytinen; Heo, 2007; Becerra; Lunnan; Huemer, 2008; Martinkenaite, 2011; Milagres; Burcharth, 2019; Schoenberg, 2001). The present paper corroborates certain mechanisms presented by previous IKT literature for other types of interorganizational partnerships, such as "contractual characteristics, "decision-making characteristics", "conflict resolution" and "lessons learned". Novel elements also emerged in the study, related to the specific context of facility acquisition, such as "transfer period", "alignment of the two companies in all working environment", "responsibility for the transfer" and "training effectiveness.

Based on the challenges identified in the case study, practical guidelines for improving IKT are suggested for each stage of the transfer. Meticulous pre-transition planning is essential, including aligning onshore and offshore teams, selecting staff with transition experience, ensuring participant availability, creating a detailed plan for objectives, scope, roles, materials, mechanisms, routines, documentation, prerequisites, monitoring, feedback, and conflict resolution. During the transition, leadership should regularly evaluate against objectives, balance knowledge types, standardize where possible, address complex areas, ensure adequate time, and document lessons. Post-transition, leadership should compile lessons learned and feedback to codify best practices and ineffective strategies, establishing a systematic approach for future codification.

The study has limitations that warrant consideration in future research. Notably, due to Company A's non-participation, the findings only reflect perspectives from Company B, hindering a comprehensive evaluation of the source company's perception within the study's context. Future research may explore the differences between the two company's perspectives. While the interviews focused on IKT issues, respondents raised concerns about broader aging issues like material degradation and obsolescence. Thus, there is an opportunity for future studies to explore the connections between these issues. Although the identified 1st order constructs are related to both onshore and offshore environments, challenges were focused on the offshore environment, as it was more complex and less structured. Given their significance in IKT, future studies should examine and compare knowledge transfer challenges in both environments. Lastly, the study identified potential consequences of knowledge transfer failure but did not explore its impact on operations. It is important that future studies analyze operational performance and the possibility of compromising safety of subsequent operations.

4. INVESTIGATING THE IMPACTS OF KNOWLEDGE TRANSFER BETWEEN OIL AND GAS COMPANIES ON PROCESS SAFETY

While recent studies have explored various challenges related to ageing oil and gas facility acquisition, the impact of interorganizational knowledge transfer (IKT) on the essential safe operation of these facilities has not been explored. This focus on IKT for process safety is paramount as the number of oil and gas facilities acquired for life extension by smaller companies has increased in recent years. The objective of this study is to identify potential consequences of unsuccessful IKT for process safety when an asset is acquired and no personnel is transferred. Semi-structured interviews were conducted with experts, who were presented IKT challenges observed in a case study of an oil platform acquisition. The findings reveal specific Risk-Based Process Safety elements that were impacted, including Process Knowledge Management, Hazard Identification and Risk Analysis, and Conduct of Operations. These findings support the development of improved IKT frameworks by managers, as well as oil and gas regulators, enabling risk management to avoid adverse impacts to the environment and the community. They also indicate the need to fill current regulatory gaps to ensure the commitment and shared responsibility of both seller and buyer companies to guarantee process safety in newly acquired ageing assets.

4.1 Introduction

Knowledge transfer between oil and gas companies is especially challenging during the acquisition of facilities for extended operation. The acquisition of oil and gas facilities has increased in recent years, as acquiring companies seek to operate these facilities beyond their useful life (Ferreira *et al.*, 2020). While this approach is less costly than building new facilities, the operation of ageing assets is known to involve various challenges, including material, obsolescence, and organizational issues (Hosktad *et al.*, 2010). Interorganizational knowledge transfer (IKT) stands out as the main organizational challenge (Ferreira *et al.*, 2024). While IKT helps ensure safe operations, this process remains poorly comprehended. The limited understanding and potential failure in this knowledge transfer represent an underestimated safety risk for operations involving ageing assets and exposure to the subjective interpretation of guidelines, that could lead to adverse impacts to the environment and the community (Wu; Olson; Birge, 2013).

While knowledge has been shown to be essential for increasing process safety (Li; Poppo; Zhou, 2010; Klein, 2012) the negative impacts of IKT, if not performed correctly, to process safety have not been explored in previous studies. With regards to regulations, neither the Brazilian, UK nor the Norwegian regulators have guidelines for evaluating knowledge transfer between companies, nor organizational issues as a whole (CCPS, 2007; ANP, 2007; HSE, 2014; Norwegian Oil and Gas Association, 2017; Ferreira *et al.*, 2020). This lack of regulation demonstrates how challenging it is for regulators to develop guidelines and for companies to understand knowledge transfer issues and tangibly assess them. Furthermore, without regulations, organizations are less likely to prioritize addressing these issues (Haynes *et al.*, 2018).

Ferreira *et al.* (2024) studied IKT for asset transfer between oil and gas companies but did not consider its outcomes. While focusing on the IKT challenges for the offshore environment, they pointed out that the onshore environment may differ and unpacking these two environments is key to identifying the challenges for IKT and its impacts to process safety (Ferreira *et al.*, 2024). In the analysis of internal knowledge transfer Conceição *et al.* (2019) and Nesheim and Gressgård (2014) recognized the operating (offshore) and engineering design department (onshore) as separate work systems or environments whose communication and alignment were essential. However, the existing IKT literature generally addresses knowledge transfer at a company level; the uniqueness of different internal environments and departments has not been considered (Milagres; Burcharth 2019).

Given the context of IKT in the acquisition of oil and gas ageing facilities when the transfer of the asset is not accompanied by personnel transfer, and the gaps in the literature and in regulation mentioned before, the following key research question is addressed: “Based on the identified challenges in the onshore and offshore environments, what are the potential consequences of an unsuccessful interorganizational knowledge transfer for process safety?”

To answer this research question, this study begins by reviewing the body of knowledge and noting the gaps in previous IKT literature with regards to process safety (Section 4.2). Section 4.3 describes the case study and qualitative approach selected. Section 4.4 first presents the challenges identified for the onshore environment and relates the challenges of both onshore and offshore environments to vulnerabilities in process safety. Based on the combination of challenges, findings related to the potential consequences to process safety are described. Implications of these findings are discussed in Section 4.5 and overall conclusions in Section 4.6.

4.2 Theoretical Background

Knowledge transfer is the process of sharing and disseminating knowledge between individuals, groups or organizations. The main goals and benefits of knowledge transfer are to improve performance, build competitive advantage, and generate innovations (Vrabcová; Urbancová; Petříček, 2021; Inkpen, 2022). An unsuccessful knowledge transfer leads not only to reduced benefits but also to significant losses, such as a loss of knowledge due to staff turnover or discontinued collaborations (Argote *et al.*, 2000), decline in operational performance (Inkpen, 2008), or even threats to the health and safety of workers (Haynes *et al.* 2018; Duryan *et al.* 2020). Furthermore, knowledge transfer can be used strategically to develop improved systems that are less prone to safety incidents (Conceição *et al.* 2019).

In IKT there is a significant heterogeneity in the extent to which companies can capture knowledge, whether in alliances (Milagres; Burcharth, 2019; Martinkenaite, 2011; Becerra; Lunnan; Huemer, 2008; Cheung; Myers; Mentzer, 2011; Schoenberg, 2001), company acquisitions (Martinkenaite, 2012; Schoenberg, 2001), mergers (Yoo; Lyytinen; Heo, 2007), collaboration with supply chain (Whitehead; Zacharia; Prater, 2019) or with academia (Chakraborty; Persis; Mahroof, 2024), as they greatly depend on context (Milagres; Burcharth, 2019). For effective and rapid learning it is crucial to establish long-term commitment among the partners, allocate time and resources for sharing tacit knowledge, ensure collaboration among partners with different strategic priorities, and share knowledge in real-time (Chakraborty; Persis; Mahroof, 2024).

In our context of facility acquisition, redeployable knowledge may be (1) generic, (2) specific to the facility and adapted to the needs of any organization taking on its operation, or (3) require adaptation to meet the context of the buying company. In any case, there is an information asymmetry whereby the seller has more knowledge about the asset acquired (Flickinger; Klarner, 2016), which makes trust essential for the sale, and knowledge transfer key to the continued operation of the asset.

Overall, IKT leads to more knowledgeable teams, which are better at identifying and managing risks (Temple; Landaeta 2020). By propagating information on potential hazards as well as risk assessment and management approaches, knowledge transfer allows lessons learned to be incorporated into processes (Zimpel-Leal; Lettice 2021), controlling potential hazards (Noruzi *et al.*, 2020). With regards to processes, Klein (2012) noted that sharing insights from incident investigations and audits promote organizational learning to avoid recurrences. Furthermore, knowledge transfer has been found to cultivate strong process safety culture across an organization, through responsibilities of safety (Klein, 2012). A failure of knowledge transfer may cause critical information to be lost, creating risks (Maier; Bayer, 2006) to employees, as well as to the public and the environment (CCPS, 2007).

4.2.1 Risk-based process safety and knowledge transfer

Without knowledge and information, workers are unable to ensure adequate and safe system operations. In the case of complex sociotechnical systems, such as oil and gas facilities, Hollnagel (2014) notes that undesirable outcomes are often caused by the interaction of multiple factors. The complex combination of dynamic factors and variability of everyday performance makes the real work less stable. Predicting this variation and increasing the worker autonomy to make necessary adjustments, is key to risk prevention of major events that can cause damage to the environment and human health (Cui *et al.* 2022). Different preventive methodologies, such as the Swiss cheese model (Reason, 2008) or the bow-tie diagram (CCPS, 2018) also demand worker knowledge and adequate information-sharing.

Risk-Based Process Safety (RBPS) is an established methodology for analysing varying hazards and risks in an operational context. The methodology gained recognition for its role in diminishing the potential for major accidents and enhancing overall operational excellence within the process industry. RBPS advocates for a risk-based resource allocation strategy (CCPS, 2007), which can be applied to diverse operations, such as the production, utilization, or manipulation of hazardous materials or energy sources. Thus, RBPS is well suited to sectors such as the oil and gas industry, which are complex and have multiple stakeholders. In this industry, enterprise safety protocols, industry benchmarks and regulations (Australia OFfice of Parliamentary Counsel, 2009; United Kingdom Statutory Instruments, 2015; ANP, 2017; United States Bureau of Safety and Environmental Enforcement, 2023) are aligned to enable the integration of management systems, improve process safety, avoid accidents (CCPS, 2007) and drive sustained success (Nunhes; Ferreira Motta; De Oliveira, 2016).

The Center for Chemical Process Safety (CCPS, 2007) defined a framework for managing RBPS, encompassing four pillars: 1) Commit to process safety, 2) Understand hazard and risk, 3) Manage risk and 4) Learn from experience. The elements of each pillar are presented in Table 4.1. Knowledge, learning, and competency permeate through each of the RBPS elements and can impact them either directly or indirectly. Despite the clear role of knowledge in RBPS, the impact of an unsuccessful knowledge transfer to these pillars and elements has not been studied.

Table 4.1 - Process Safety Management Framework for Risk Based Process Safety (RBPS)

RBPS Pillar	RBPS Element
Commit to Process Safety	Process Safety Culture Compliance with Standards Process Safety Competency Workforce Involvement Stakeholder Outreach
Understand hazard and risk	Process Knowledge Management Hazard Identification and Risk Analysis
Manage risk	Operating Procedures Safe Work Practices Asset Integrity and Reliability Contractor Management Training and Performance Assurance Management of Change Operational Readiness Conduct of Operations Emergency Management
Learn from experience	Incident Investigation Measurement and Metrics Auditing Management Review and Continuous Improvement

Source: Based on CCPS, 2007

To illustrate the role of knowledge in RBPS, a few relevant elements are described. For example, the RBPS element of process safety competency is established through three interconnected actions: continuously improving knowledge and competency, ensuring that appropriate information is available to people who need it, and consistently applying what has been learned (CCPS, 2007) The RBPS element of process knowledge management focuses on organizing explicit knowledge through tasks such as compiling, categorizing, and providing access to data (CCPS 2007). Information that cannot be efficiently accessed or that might be confused with other information, leads to disorder. And disorder in critical processes is a hazard. (CCPS 2007).

Another RBPS element with clear knowledge contribution is operating procedures, which comprises formally documented and sanctioned methods designed to mitigate the risks associated with dependence on memory. Sharing procedures and defining new responsibilities for these procedures are essential to knowledge transfer (CCPS 2007). Moreover, the RBPS element training and performance assurance is two-fold, i.e. learning and testing, both fundamental to knowledge transfer. Beyond these examples, other RBPS elements are also connected to knowledge transfer. Actions such as "involve competent personnel", "update information", "apply knowledge", "determine what training is needed", "qualify workers", "train works", "train workers to recognize hazards", "train workers to self-check and peer-check" are stated in the elements of Hazard Identification and Risk Analysis, Safe Work Practices, Asset Integrity and Reliability, Management of Change, Operational Readiness and Conduct Operations (CCPS 2007). Thus, all RBPS pillars and elements were considered in the present study in identifying the potential impacts of IKT when an asset is transferred but not the personnel.

4.3 Material and Methods

This research analyses knowledge transfer between two companies in the oil and gas industry during the acquisition of an ageing facility for life extension, whereby only the asset and related documentation was transferred, not the personnel. Given the motivation to thoroughly investigate a specific scenario, i.e. the impact of IKT on process safety in the context of oil and gas facility acquisition for life extension, a case study approach was deemed fit (O'leary, 2005). The case study uses data collected by Ferreira *et al.* (2024). Whereas these authors identified IKT challenges only for the offshore environment, herein onshore challenges are identified to provide a full perspective of IKT for the analysis of process safety implications. Thus, the research is divided into two steps 1) identification of IKT challenges onshore, extending upon already identified offshore challenges; 2) evaluation of the impact of these challenges in both environments on safety based on interviews with process safety experts. The case study system considered in both steps is the same.

4.3.1 Research context and case study selection

The selected case study considers an ageing offshore production facility in Brazil, "Platform X", operational since 2006 and slated to operate until 2025, originally studied by Ferreira *et al.* 2024. The platform was initially owned by Company A (the source of knowledge) and was acquired by Company B (the recipient) who intends to extend the platform's operation in the future. Both companies are based in Brazil, with Company A being markedly larger than Company B. No personnel were transferred from Company A to Company B, which is common practice for Company A. The transition in ownership occurred during these 6 months. Company B took over the sole operation of the platform in January 2023 ("Day 1" henceforth).

Knowledge transfer between companies took place within two distinct environments - offshore and onshore. These two environments differ not only in location but also in their roles and organizational structures during the asset transition. The onshore environment comprised the corporate aspects of both companies and the support functions associated with offshore operations. In this environment, both companies organized around specific "Work Streams" (WS) for knowledge transfer, such as Health, Safety and Environment (HSE), Subsea, Field Operations, etc. Each WS had designated leaders from both companies guiding the transfer. In upper level, each company also had transition managers (TM), and a steering committee.

4.3.2 Data collection

The first step of the research began by analyzing data from Ferreira *et al.* (2024), who interviewed professionals at Company B in various settings, as Company A opted out of the study. These semi-structured interviews, focusing on the transition period, yielded eight onshore transcripts for analysis, excluding offshore challenges previously identified by Ferreira *et al.* (2024). The participants spanned three hierarchical levels: top managers, middle managers, and employees, detailed in Table 4.2.

Table 4.2 - Characteristics of interviews – knowledge transfer (onshore)

Position during transition [1]	**Hierarchical level**[2]
Transition Manager	TM
Coordinator of WS Field Operations	MM
Coordinator of WS Engineering, Maintenance, and Integrity	
Coordinator of WS Naval	
Coordinator of WS HSE (Heath, Safety and Environment)	
Coordinator of WS Drilling and Wells	
Coordinator M&A (Merge and Acquisition)	
Automation engineer	EM

[1]One interview session was conducted with each interviewee. [2]TM - top manager; MM - middle manager; EM – employee.
Time of interviews – 13:34h; Pages of transcription in Times New Roman, font size 12, single space – 355

Source: Based on Ferreira *et al.,* 2024

In the second step of the research, a new set of interviewees was chosen to discern potential impacts of the identified IKT challenges on process safety. Because the literature regarding this topic is limited, a qualitative, inductive, and exploratory research approach is warranted (Creswell; Mallmann, 2014). Six specialists were selected using the snowball approach (network sampling) (Goodman, 1961), a widely accepted technique for choosing and reaching experts recognized by their peers for having relevant knowledge for the research. The interviewees hold top and middle level managerial positions and long careers (more than 10 years) in the oil and gas industry, represent diverse stakeholders (regulator, operator, and consultant), have performed management and problem-solving activities related to operational and process safety, and have experienced asset transition in the oil and gas industry from different perspectives (Table 4.3). After the interviews, a significant amount of repetition and overlapping of elements was found, pointing to the relevance of the findings and indicating that the point of saturation was reached.

Table 4.3 - Characteristics of interviews with process safety experts

Organization	**Expertise**[1]	**Hierarchical level** [2]
Regulatory agency	Risk, Safety and Human Factors	TM
Petrochemical company	Risk analysis and Reliability Engineering	
Consulting company	Asset management	
Consulting company	Risk, Safety Culture and Human and Organizational Factors	MM
Oil and gas exploration and production company	Risk and Safety	
Chemical Center for Process Safety (CCPS)	Industrial Risk Management	

[1]One interview session was conducted with each interviewee.; [2]TM - top manager; MM - middle manager; EM – employee.

Time of interviews – 11:01h; Pages of transcription in Times New Roman, font size 12; single space – 365

Source: The author, 2024

To facilitate in-depth exploration, a semi-structured protocol featuring open-ended questions was employed. This approach encouraged interviewees to offer detailed descriptions and to add issues not initially included in the protocol (Stewart; Cash; Cash Jr, 2015). The process safety experts were first presented with the context of the case study and then findings from the first research step were presented. Each IKT challenge for both environments was explained by summarizing the related case study issues with quotes derived from the original interviews. After each challenge, the expert was asked two questions: *1) Do you think this knowledge transfer challenge could impact process safety? 2) If yes, how?* The process safety consequences, as identified by the experts are extensively examined in Section 4.4 of the study.

The process safety expert interview protocol was validated in the first of six interviews. Through this validation, one-on-one interviews were found to be most effective to enable experts to quickly provide feedback after each challenge and were used throughout the data collection. The interviews were conducted online with Microsoft Teams, with an average duration of two hours, and were recorded with the permission of the interviewees. Interviews were transcribed electronically using Microsoft Teams. Manual notes were also taken during the interviews by the three interviewers regarding key points presented.

4.3.3 Data analysis

In the first step of the research, the onshore interview transcripts were organized according to 22 IKT elements, and 10 IKT constructs, as defined by Ferreira *et al.* (2024) (Table 4.4).

Table 4.4 - IKT constructs and IKT elements

STRUCTURAL GOVERNANCE
1) Contractual characteristics 2) Decision-making characteristics 3) Conflict resolution 4) Transfer period 5) Alignment of the two companies in all working environments
RELATED ABSORVITIVE CAPACITY
6) Degree of similarity
MOTIVATION
7) Availability 8) Proactivity 9) Provision of resources
PRIOR EXPERIENCE
10) Previous experiences 11) Lessons learned
TRAINING
12) Identification of training needs 13) Training effectiveness
MANAGEMENT CAPACITY
14) Transfer objectives 15) Transfer scope 16) Responsibility for transfer 17) Evaluation mechanism & method
INTER-ORGANIZATIONAL ROUTINES
18) Definition of routines
OTHER COORDINATION TOOLS
19) Access to databases 20) Mechanisms used
TIME
21) Collaboration duration
DUE DILLIGENCE
22) Due diligence for knowledge transfer

Source : Based on Ferreira *et al.*, 2024

Based on these constructs, a comprehensive content analysis of the transcribed interviews was conducted to provide a systematic, and qualitative description of the communication content (Schreier, 2012). Similar to the approach of Ferreira *et al.* (2024) for the offshore environment, quotes with a negative connotation were identified as being related to challenges. For each IKT element, key challenging themes were inductively identified and coded as challenges for the onshore environment (IKT challenges). The identified onshore challenges were then juxtaposed with the offshore findings of Ferreira *et al.* (2024) to spur the discussion in the second step of the research.

In the second step of the research, the process safety expert interview transcripts were analysed (Schreier, 2012). This analysis focused on the empirical and technical elements of the experts' description. The goal of this was to understand concrete causalities and systemic effects of the IKT challenges on process safety, based on their experience. The interview transcripts were manually treated using Microsoft Excel. Firstly, the transcripts were organized according to the 22 IKT elements. Then, expert quotes related to the impacts of process safety were isolated. Repetition and exemplification of the challenges by the experts was taken as agreement and confirmation of the findings of the first step. Lastly, for each highlighted statement the most closely associated RBPS element was identified. Similarities in the process safety experts' discourse was used to confirm the most relevant associated RBPS elements for each IKT construct.

4.4 Results

The findings from the first step of the research are explored in section 4.4.1 and provide perspective on the IKT challenges for both onshore and offshore environments. Based on these IKT challenges, the potential implications of a failure in IKT to process safety are explored in section 4.4.2.

4.4.1 Challenges of IKT in the onshore environment and comparison to offshore

The following subsections are defined according to the 10 IKT constructs and explain each IKT element, in the context of the onshore environment and draw attention to relevant challenges, in bold, based on illustrative quotes from the onshore interviews.

4.4.1.1 Structural Governance

Contractual characteristics. The contract for facility acquisition was the responsibility of the onshore personnel. It established general activities relative to IKT. However, the lack of details on expectations of documents, timing, and resources for IKT, led to a **misalignment between this instrument and operational requirements:** "...if we were to use the contract as it was written, we would have had a lot of difficulty in transferring knowledge and operating the asset." (MM)

The use of **generic statements with ill-defined requirements and deadlines** led to the following issues: 1) subjective content sharing; 2) information and documents mostly shared just before day 1, rather than gradually; 3) Company A, not required to disclose all procedures for Platform X, withheld documents relevant to its other platforms; 4) limited offshore access for Company B (only 4 employees compared to about 200 from Company A); 5) lack of prior testing for the unit's safety-related systems.

> For the shadowing period, we began negotiating the participation our on-board personnel, but only a total of 4 people simultaneously were accepted, which did not meet our needs in terms of knowledge transfer opportunities. In practice, we had almost 50 people on board. If we were to follow the contract in this regard, we would be in trouble. (MM)

Decision-making characteristics. Decision-making in the onshore environment was carried out within each WS and was generally consensus driven. Challenges were found to be of the same nature as the offshore environment, i.e. **unilateral decision-making contrary to the effectiveness of knowledge transfer** (Ferreira *et al.*, 2024). However, the onshore situation varied, marked by Company A's firm stance against: 1) more frequent WS leader meetings; 2) Company B's involvement in technical analyses; 3) Company B testing key safety systems before Day 1; and 4) sharing procedures with Company B, unless specific to the transitioning unit: "Permission to test the PI system [an operational support system that visualizes plant parameters] during the transition was not granted, even though we demonstrated that it was possible to conduct the test separate from the Company A system... As a result, we entered Day 1 with a high-risk component." (MM)

Conflict resolution. Unlike the offshore environment, the onshore had a structured process for conflict resolution. The process, endorsed by both companies, consisted of 3 steps: 1) internal within the WS; 2) internal between company transition managers; 3) internal with a steering committee. However, the parties were **unable to resolve conflicts within the established framework, requiring regulator involvement**. "We took the conflict associated with well tool access to the steering committee, but it was the regulatory body (ANP) that ultimately helped resolve the deadlock." (MM)

This resulted in the unforeseen expenditure of time and energy to resolve issues that could have been settled through consensus between the two companies.

Transfer period. The challenge in the onshore environment, was the same as onshore, i.e. **unpredictability of the knowledge transfer period** (Ferreira *et al.*, 2024). The date established in the contract for the facility transfer underwent multiple postponements, leading to rework.

> The lack of visibility regarding dates, coupled with the shortage of dedicated personnel, led to rework. When the closing was scheduled for November, the maintenance team began migrating the inspection and maintenance plans in September, but they had to redo them again in December, just before the pre-closing... a massive amount of work. (MM)

Alignment of the two companies in all working environments. Based on the interviewers, the working environments were well aligned, with no challenges being identified. Despite this perception, offshore personnel complained of a lack of transparency in decisions made by the onshore environment (Ferreira *et al.*, 2024).

4.4.1.2 Related absorptive capacity

Degree of similarity between companies. Similar to the offshore environment, onshore teams were **unable to resolve differences** (Ferreira *et al.*, 2024)**.** Relevant differences included: 1) autonomy of onshore personnel (standardized vs. less standardized/more room for creativity); 2) systems (customized vs. standard); 3) control room structure (remote with fiber optic resource availability vs. onboard; 4) methodologies used for technical analyses. These differences negatively impacted the understanding and exchange process, requiring more time for tasks such as migrating information systems.

> Company A's integrity management system was highly customized while ours was more standardized... we realized during the process that we must do a lot of

> migration of systems…time-consuming and labor-intensive. In conclusion, we conducted a fast-paced system migration, and we continue to experience issues to this day. (MM)

4.4.1.3 Motivation

Availability of companies. The availability of Company A personnel varied significantly by WS, with some unwilling to increase the length or frequency of interactions. This lack of flexibility reflected the **low priority given to scheduling of knowledge transfer,** similar to the offshore environment (Ferreira *et al.*, 2024). "Outside of the weekly 1-hour meetings, it was challenging to access individuals." (MM)

Proactivity of companies. Interview participants perceived Company A to be significantly less proactive than Company B. Similar to the offshore environment, there was an **unstructured knowledge transfer, reliant on questions,** and a **misunderstanding of shared knowledge transfer responsibility** (Ferreira *et al.*, 2024). "The meetings were more of a "question and answer" format, relatively unstructured, and Company A didn't proactively contribute anything (the role of bringing up key issues wasn't assigned to Company A, and things were often "discovered" through casual conversation)." (MM)

Provision of resources. Both companies struggled with the **lack of dedicated team for knowledge transfer,** similar to the offshore environment. Most of the Company B WS leaders were involved with other company assets, and were not fully dedicated to the IKT, making the process slower and more difficult. "We hired only one engineer in the WS who was 100% dedicated to the transition, but the rest of the team continued to divide their time... so this engineer was the only one who truly analyzed the report content (gained knowledge)...there was a lack of capacity for effective knowledge transfer." (MM)

4.4.1.4 Prior experience

Previous experiences. Both companies' onshore leadership had experience conducting facility transitions, yet with other companies. While Company B's operational personnel also had facility transition experience, Company A had **limited experience in asset transition,** a challenge recognized offshore (Ferreira et al, 2024).

> The experience depended on the interlocutor from Company A. The corporate personnel had a lot of experience due to their participation in other transitions. However, the business unit personnel had no previous experience, and this sometimes rises some problems, regarding how to involve people and carry out the process of knowledge transfer. (MM)

Lessons learned. Unlike the offshore environment, onshore staff from both companies applied lessons from past projects. Company A's insights involved organizing IKT with WS and weekly meetings, using a steering committee for conflict resolution, and developing tool-sharing methods within the asset. Company B's contributions included a verified system migration roadmap, improved information organization and tracking, and identifying essential pre-existing documentation. These lessons were consolidated in a document called "Operated Asset Transition Management." Nonetheless, Company B’s practices did not match the expectations set by this document, indicating an **incompatibility between practices and lessons learned**.

4.4.1.5 Training

Identification of training needs. In most cases, Company B did not recognize the need for training to be provided by Company A or did not realize that they could request training from them, as in the offshore environment (Ferreira et al, 2024). The **lack of understanding that training from the source company is a means of acquiring knowledge** resulted in Company B resorting to other sources of knowledge, such as suppliers and individual professionals.

> I would have liked to have a more in-depth explanation or technical discussion with Company A`s technicians to better understand the onboard systems... but I got the sense that they were unavailable or didn't see it as their role to provide that kind of support. So, we opted to hire a professional who had been involved in the development of one of the systems (that we have some issues) to assist us in brainstorming potential solutions to the problem we were facing. (EM)

Training effectiveness. Upon request, Company A offered training in accordance with its availability. Based on the interviewers, this training greatly aided in the absorption of knowledge, with **no challenges being identified.** This was also the case for the offshore environment (Ferreira et al, 2024).

4.4.1.6 Management capacity

Transfer objectives. While the onshore transition managers for Company B provided initial directions to the WS leaders, which was more guidance than in the offshore environment, the leaders still felt "lost". The **unclear definition of objectives** remained a challenge, same as offshore (Ferreira et al, 2024).

> I received a briefing that the transition was structured into Workstreams (WS), but I didn't receive any specific guidelines on what should be addressed and how it should be handled within the WS. There was no material to read (such as a procedure or document) to provide me with a basis on how to conduct the transition, what type of knowledge should be absorbed. (MM)

Transfer scope. Similar to the transfer objectives challenges, initial guidance was insufficient for establishing a clear scope. **Inconsistent scope definitions,** also a challenge offshore (Ferreira et al, 2024) caused ambiguity to persist among WS leaders. This lack of clarity led to an overlap of content across WS.

> The scope of each WS wasn't initially clearly defined. It was known that the WS were defined, but the content of each WS wasn't defined. For some months, there was segmentation among WS and aggregation of content between them. For example, the inventory and process engineering aspects were initially within the Maintenance WS, then those parts migrated to other WS. (MM)

Company A's onshore team was equally unclear of their scope, as many information requests from Company B were met with hesitation from Company A. They were not sure whether the information was proprietary or not. This caused time-consuming **last-minute evaluation of documents for intellectual property restrictions before sharing**. "Many of the pieces of information we requested were scrutinized to determine whether they were Company A "intellectual property" or not. So, communication wasn't smooth. People would stop to evaluate whether they could provide the information or not." (MM)

Responsibility for the transfer. While it was clear from the beginning that the transition manager was responsible for IKT onshore, they also had responsibilities with other

Company B assets. “The transition manager was both the engineering manager and the transition manager simultaneously. I recall a specific situation (a serious issue on another vessel in the fleet) where he had to be almost completely absent from the transition.” (EM)

This **lack of dedicated personnel to focus on and coordinate knowledge transfer** caused a **poor interface between offshore and onshore teams,** as identified previously (Ferreira et al, 2024). Furthermore, the onshore transition manager did not have the time to monitor and support each WS, creating a **poor interface between WS** as well.

Evaluation mechanism and method. Different from the offshore environment, systematic and formal mechanisms were established onshore to monitor the IKT, such as weekly meetings between the WS and the transition manager, as well as monthly updates to the steering committee. However, these updates and the overall IKT **evaluation focused on documentation, ignoring other knowledge transfer aspects.** Even though each document listed in the Transition Plan led to various actions and activities for the WS leaders, these were not tracked. Follow-up was left to the discretion of each relevant coordinator, creating gaps in monitoring.

> The Transition Manager monitored the KPIs for document delivery, how many had been validated and approved by the WS leaders. But he didn't have insights into other matters, like software, licenses, what had already been migrated, what was left to learn, what needed to be done only on Day 1, or if resources were lacking for knowledge absorption. (MM)

4.4.1.7 Inter-organizational routines

Definition of Routines. Formal routines were established between the onshore teams of both companies, primarily consisting of weekly WS leader meetings. However, these routines often did not go beyond updating the Transition Plan, such as tracking ongoing activities and the status of action plan implementations, understanding existing asset plans, or providing a comprehensive overview of the asset's operations. Thus, **the routines established did not cover all aspects of knowledge transfer.**

> Weekly meetings were established with the aim of following up on the Transition Plan... Company B would present documentation pending and negotiate new

> delivery dates with Company A... In these meetings, doubts were clarified, and specific individuals were requested. (MM)
>
> Sometimes information requested in one WS would appear in another WS, so we had to go and retrieve it from colleagues... but it took time to identify where it was located. It was a real information retrieval process. (MM)

4.4.1.8 Other coordination tools

Access to databases. Company A's WS leaders managed information dissemination, uploading data to Microsoft Teams, a platform selected by Company A but occasionally incompatible with file sizes, causing errors and repeated download attempts, thereby increasing rework. A document controller organized and filtered the documentation for Company B's WS. However, much of the shared content was outdated and failed to reflect the facility's current state accurately. The transfer of documents did not run smoothly either due to an **inefficient batch approach to information sharing**. This approach did not align with the transition requirements, resulting in delays in data/information exchange and difficulty in assimilating the provided documents.

> The documentation transfer didn't work well due to the size of the files. We took a long time to access them because of the transfer method. We suggested that someone from IT bring a physical hard drive to Company A’s office. But that wasn't accepted... they seemed to prefer a more formal approach. (MM)
>
> It took an enormous amount of time to find information about the supervisory system because these details came within a batch of project documentation (a large volume) and in a format we were unfamiliar with. (EM)
>
> There was a large batch of documents at the beginning, then it came to a standstill... and then, one month before Day 1, an enormous volume of information arrived that was very challenging to digest. (MM)

Mechanisms used for knowledge transfer. Knowledge transfer onshore was primarily based on dialogue between the leaders of both companies during weekly WS meetings. However, these meetings were unstructured, they did not provide an overview of priority issues for Company A, nor explanations of the data being transferred. Outside these meetings, three workshops for knowledge transfer were held. These did not evolve into recurring mechanisms for IKT, despite Company B's expressed intent to maintain them throughout the process. “Workshops between Company A and B within some WSs were very beneficial for knowledge transfer. The only issue was that Company A didn't agree to do this continuously. We saw this as an alternative form of knowledge transfer that in other transitions occurred through "desk discussions." (MM)

The **restricted and unstructured mechanisms for transfer between companies** prompted Company B to seek alternative and more costly methods to obtain information, such as from suppliers and consultants.

4.4.1.9 Time

Set Collaboration Duration. The **lack of a detailed plan to accurately estimate time required,** as also identified for offshore environment (Ferreira et al, 2024), meant that in several WS, time was only sufficient for receiving and verifying the completeness of the received documentation. Assimilation and absorption were postponed to a later stage, once the unit was already in operation. “Three months would have been sufficient, if all the documentation were delivered in advance or gradually.” (MM); “The Company A`s staff also weren't fully dedicated, which made internal information retrieval slower and communication moments scarcer.” (MM); “I would have liked to have more time to digest all the data we received. Certainly, the quality of the analyses would have been better. Considering the size of the asset (the largest we've ever had), having more time would have been worthwhile.” (MM)

4.4.1.10 Due Diligence

Due diligence for knowledge transfer. The due diligence process failed to highlight potential differences between the companies that could have facilitated IKT planning. Instead, **due diligence focused only on economic aspects, not including knowledge transfer**.

> “...there was due diligence, but it didn't provide any inputs to the WS.” (MM)
> “The idea behind the due diligence was to determine if the business made sense commercially. Other issues such as the unit's degradation, or the ease or difficulty of transferring knowledge, were to be handled by Company B later on. In other words, it didn't offer inputs for the transition phase or a prior assessment.” (MM)

Comparing the above-mentioned challenges of the onshore environment with those presented by the authors Ferreira *et al.* (2024), as shown in Table 4.5, it can be observed that 12 of the 24 onshore challenges coincided with the offshore challenges. However, the reasons underlying them are specific to each environment. Unpacking their causes and consequences is essential to understanding their process safety impacts, as described in the next subsection.

Table 4.5 - Overview of challenges for onshore and offshore environments

<table>
<tr><th rowspan="2">IKT Construct</th><th rowspan="2">IKT Element</th><th colspan="2">IKT Challenges</th></tr>
<tr><th>OFFSHORE (Ferreira et al., 2024)</th><th>ONSHORE</th></tr>
<tr><td rowspan="5">Structural governance</td><td>1. Contractual characteristics</td><td>--</td><td>Misalignment between the contract and operational requirements.
Generic statements with ill defined requirements and deadlines.</td></tr>
<tr><td>2. Decision-making characteristics</td><td colspan="2">Unilateral decision-making contrary to the effectiveness of knowledge transfer.</td></tr>
<tr><td>3. Conflict resolution</td><td>Ad-hoc approach to conflict resolution during knowledge transfer.</td><td>Inability to resolve conflicts within established framework, requiring regulator involvement.</td></tr>
<tr><td>4. Transfer period</td><td colspan="2">Unpredictability of the knowledge transfer period.</td></tr>
<tr><td>5. Alignment of the two companies in all working environments</td><td>Lack of transparency on consensual decisions made in different environments.</td><td>---</td></tr>
<tr><td>Related absorptive capacity</td><td>6. Degree of similarity between the companies</td><td colspan="2">Unable to resolve differences.</td></tr>
<tr><td rowspan="6">Motivation</td><td rowspan="2">7.Availability</td><td>Competition between operational functions and those related to knowledge transfer.</td><td>---</td></tr>
<tr><td colspan="2">Low priority given to scheduling of knowledge transfer.</td></tr>
<tr><td rowspan="3">8.Proactivity</td><td colspan="2">Unstructured knowledge transfer, reliant on questions.</td></tr>
<tr><td colspan="2">Misunderstanding of shared knowledge transfer responsibility among companies.</td></tr>
<tr><td>Unwillingness to share knowledge due to resistance to acquisition.</td><td>---</td></tr>
<tr><td>9.Provision of resources</td><td>Lack of resources (software, hardware, equipment & personnel) prior to beginning knowledge transfer.</td><td>Lack of dedicated team for knowledge transfer.</td></tr>
<tr><td rowspan="2">Prior experience</td><td>10.Previous experiences</td><td colspan="2">Limited experience in asset transition.</td></tr>
<tr><td>11.Lessons learned</td><td>Lack of documented lessons</td><td>Incompatibility between</td></tr>
</table>

<table>
<tr><th rowspan="2">IKT Construct</th><th rowspan="2">IKT Element</th><th colspan="2">IKT Challenges</th></tr>
<tr><th>OFFSHORE (Ferreira et al., 2024)</th><th>ONSHORE</th></tr>
<tr><td></td><td></td><td>learned.</td><td>practices and lessons learned.</td></tr>
<tr><td rowspan="2">Training</td><td>12. Identification of training needs</td><td colspan="2">Lack of understanding that training from the source company is a means of acquiring knowledge.</td></tr>
<tr><td>13.Training effectiveness</td><td>---</td><td>---</td></tr>
<tr><td rowspan="7">Management capacity</td><td>14.Transfer objectives</td><td colspan="2">Unclear definition of objectives.</td></tr>
<tr><td rowspan="2">15.Transfer scope</td><td colspan="2">Inconsistent scope definition.</td></tr>
<tr><td>Unclear prioritization between tacit knowledge acquisition and physical asset assessment.</td><td>Last-minute evaluation of documents for intellectual property restrictions before sharing.</td></tr>
<tr><td rowspan="3">16.Responsibility for the transfer</td><td colspan="2">Lack of dedicated personnel to focus on and coordinate knowledge transfer.</td></tr>
<tr><td colspan="2">Poor interface between offshore and onshore team.</td></tr>
<tr><td>---</td><td>Poor interface between offshore and onshore teams and between work streams (WS).</td></tr>
<tr><td>17.Evaluation mechanism and method</td><td>Lack of systematic definition of evaluation tools.</td><td>Evaluation focused on documentation, ignoring other knowledge transfer aspects.</td></tr>
<tr><td>Inter-organizational routines</td><td>18.Definition of routines</td><td>Independent routines set for each company's operational teams.
Individual routines set according to availability and not for optimal knowledge transfer.</td><td>Lack of routines that cover all aspects of knowledge transfer.</td></tr>
<tr><td rowspan="2">Other coordination tools</td><td>19.Access to databases</td><td>Piece-meal sharing of documents, not based on type of function and system.
Documents not organized prior for knowledge transfer.</td><td>Inefficient batch approach of information sharing</td></tr>
<tr><td>20. Mechanisms used for knowledge transfer</td><td>Lack of alignment between mechanisms applied, knowledge type, and preferred learning style.</td><td>Restricted and unstructured mechanisms for transfer between companies.</td></tr>
<tr><td>Time</td><td>21. Collaboration duration</td><td colspan="2">Lack of detailed plan to accurately estimate time required.</td></tr>
<tr><td>Due diligence</td><td>22. Due diligence for knowledge transfer</td><td>---</td><td>Due diligence focused only on economic aspects, not including knowledge transfer.</td></tr>
</table>

Source: The author, 2024

4.4.2 Process safety implications of failure in interorganizational knowledge transfer

Based on the challenges presented in section 4.4.1, it is clear there was a failure in IKT for the onshore environment, similar to the offshore environment (Ferreira *et al.*, 2024). This failure makes the ageing asset acquisition process less efficient, less effective, more time consuming, unnecessarily complex and creates a knowledge gap for Company B. Interviewees pointed to the issue of safety related data and materials being acquired without full understanding and assimilation. However, process safety consequences were not clearly described by the respondents in the first step of the research, even though there were some indications: "Even simple, and essential things for operation and safety of the unit were made difficult for us to access." (MM).

Interviews with process safety experts unequivocally recognized consequences of the failure in IKT to process safety. Thus, the main RBPS elements impacted by the failure in each IKT element, were identified based on examples provided by the experts. The resulting list of RBPS elements impacted by each IKT element is detailed with relevant quotes for each identified element in Table 4.6.

Table 4.6 - Process safety elements impacted by challenges in IKT elements

IKT Element	*Process Safety Expert Quotes*[1]	RBPS Elements
1. Contractual characteristics	The lack of detail in the contract, which resulted in Company B not receiving the **emergency response procedure**—something essential for operations—caused it to lose all the knowledge behind the procedure. Additionally, during the phase of assisted operation, how would the interaction between the groups of the two companies occur in case of an emergency? Theoretically, the "new procedure" of Company B would be in effect, which, in turn, is not understood by the people from Company A who were on board. (MM)	Emergency Management
	The absence of relevant documentation can disrupt a **maintenance strategy** that has been adopted in the asset, impacting the understanding of **risk analyses,** and the experiences of the unit. This can lead to problems with loss of containment in the future. (TM)	Asset Integrity and Reliability Hazard Identification and Risk Analysis
	In the absence of tacit knowledge, those who received the asset lack the capability to document this knowledge in **operational procedures** that would ensure the safety of operations. (TM)	Operating Procedures
	A generic contract hinders the understanding of the object of the purchase/sale for both companies, causing the team from Company A, responsible for operationalizing the knowledge transfer, to be unsure of what they can and should do. This results in **personnel avoiding the transfer of information** they consider more sensitive, leading to the loss of essential information for the safe operation of the plant. (MM)	Workforce Involvement
	When the contract stipulates that only 4 people are allowed on board from Company B to acquire knowledge of an entire facility, it indicates that those who drafted the contract did not grasp the concept that, for instance, most of the knowledge is absorbed through practical experience. This demonstrates a lack of understanding of the operational needs of Company B, impacting, for example, **compliance with standards**. (MM)	Compliance with Standards
2. Decision-making characteristics	The decision against granting full testing permission for the operation and **safety support systems** resulted in the systems that were available to Company A becoming unavailable to Company B from day 1. This has led to a lack of **reliability regarding the** integrity of critical elements of operational security. (MM)	Asset Integrity and Reliability
	If Company B did not have the possibility to monitor and track process variables (because was not authorized to do the test before day 1), all **operational routines** (resulting from this monitoring) are affected. (MM)	Conduct of Operations
	By not participating in the decision-making process to **understand the state of the systems** and how certain decisions were made, the opportunity to build a **situational awareness** that Company B needed from day 1 was lost. From that point, they could have anticipated	Hazard Identification and Risk Analysis

IKT Element	*Process Safety Expert Quotes*[1]	RBPS Elements
	problems and facilitated future decision-making. (MM)	
4. Transfer period	When people's frustration leads to a loss of transparency in the knowledge transfer process, the implications for the safety of operations are directly related to the **information and knowledge that was not transferred**. This can have a decisive impact, for example, on the **qualification of individuals** to operate the asset. (TM)	Process Knowledge Management
	Personal relationships deteriorate, and this impacts everything related to the **"how to do it**," the essential insights that may not be passed on, affecting the **execution of procedures**, for example. (MM)	Operating Procedures
6. Degree of similarity between the companies	Therefore, considering that Company B has to comprehend and transition from a complex procedure with numerous references to other procedures of Company A to a simpler and more generic procedure that the team from Company B is more familiar with, undoubtedly, in this process, operational information will be lost, and **operational knowledge** acquired from the asset will be forfeited. (MM)	Operating Procedures
	The difficulty in resolving differences in terms of systems, such as **mechanical integrity systems**, led to the loss of historical information on the integrity of certain equipment. This compromises the **understanding of their physical condition** and introduces greater uncertainties for subsequent maintenance. (TM)	Asset Integrity and Reliability
7.Availability 8.Proactivity	There will be **operational problems** outside the radar of Company B, as if they were starting to operate with "untested" new procedures, almost like theoretical procedures, lacking the necessary tacit knowledge and historical understanding accumulated in the asset. (MM)	Conduct of Operations
	Knowledge transfer doesn't happen just by exchanging documents; interaction is crucial, especially due to the specificities and the entire operational history. The lack of proactivity from Company A damages the relationship between the companies and almost renders the **transfer of tacit knowledge ineffective**. (TM)	Process Knowledge Management
	The pace of the transfer, being determined by the inquiring company (Company B), meant that those **least knowledgeable about the installation were leading the process**. This increased the likelihood of knowledge loss significantly. (TM)	Workforce Involvement
	The lack of organization in the knowledge transfer by Company A results in Company B being unaware of changes that may have occurred in the unit. For instance, in the case of an old unit, there were likely degraded systems that triggered change management processes. However, these changes may not be understood by Company B, making it impossible to **manage the risks associated with these changes**. (TM)	Management of Change
9. Provision of resources	...because when I don't have the people, I still don't have the structure that will be able to absorb this knowledge. So, it has a general impact on safety because, once again, I won't have the competencies as people won't **know how these systems can be operated**. (MM)	Conduct of Operations

IKT Element	*Process Safety Expert Quotes*[1]	RBPS Elements
12. Identification of training needs	The opportunity to learn from those who are most familiar with the day-to-day operations of the unit was missed (which, in the case of an old facility, may not be the supplier). Training would have been one of the ways to foster **competence development**. (MM).	Process Knowledge Management
14.Transfer objectives 15.Transfer scope	The clear **definition of roles and responsibilities** regarding the knowledge transfer process is essential to accommodate the **time constraints and availability of professionals involved**. This ensures that they can achieve the expected performance by the end of the process. (MM)	Workforce Involvement
	Without clear objectives and scopes, information will not successfully transition from company A to B. Company B will lack the necessary resources to initiate operations, and its employees will struggle to **achieve the required performance to effectively manage the asset's risks**. (MM)	Training and Performance Assurance
	Knowing the physical characteristics of the asset was only the fundamental aspect of the knowledge that should be assimilated. Tacit knowledge, especially in the case of an ageing unit, is crucial for the safety of operations and understanding the **gap between a plant "as good as new" and the plant in its current state**. The knowledge transfer was precisely intended to assist in overcoming this gap and mitigating it. If I fail to identify the gaps, I miss the opportunity to mitigate the risks of operations. (TM)	Hazard Identification and Risk Analysis
16.Responsibility for the transfer	The Transition Manager will be responsible for the transition and, consequently, for knowledge transfer. However, they must delegate to someone with expertise in knowledge management to oversee all aspects of the knowledge transfer. Otherwise, a significant amount of **knowledge may be lost in the process**. (MM).	Process Knowledge Management
	The absence of a knowledge manager led to a failure in estimating the time allocation (slot for knowledge transfer), which would have been sufficient for each person, whether onshore or offshore, to assimilate the necessary knowledge for their role. Once again, the **understanding of individuals remained incomplete** for the future operation of the asset. (TM)	
17.Evaluation mechanism and method	...if I don't even know where professionals need to reach in terms of knowledge, if I haven't defined the roles and responsibilities well for each one, the assessment is compromised. How can I **evaluate if the expected level of competence has not been established**? (MM)	Training and Performance Assurance
	If knowledge transfer is framed in terms of a schedule for document reception, the company may be able to meet deadlines. However, this process is entirely **ineffective for the actual acquisition of knowledge**, which involves understanding and assimilating the received information. In other words, a profound comprehension of the plant's processes and the associated tacit and empirical knowledge is essential. (TM)	Process Knowledge Management
18.Definition of	People found a way to become familiar with the facility and learn, which was not ideal for acquiring knowledge of the plant.	Hazard Identification and Risk

IKT Element	*Process Safety Expert Quotes*[1]	RBPS Elements
routines	Consequently, **many existing issues were not addressed**, and the knowledge was not fully assimilated. (MM)	Analysis
20. Mechanisms used for knowledge transfer	The routine should be carefully thought out and established when considering the mechanisms that the team will use to tap into the knowledge of professionals from company A, whether it's through an initial presentation, followed by on-the-job training, and so on. When this mirroring of mechanism-routine does not occur, it jeopardizes the acquisition of knowledge and, consequently, the **performance assurance of professionals** from company B. (MM).	Training and Performance Assurance
19.Access to databases	Structured documentation of the system's evolution from the design phase and how it has progressed over time needs to be conveyed in an organized and structured manner; otherwise, obtaining the necessary information for **understanding the systems' operation** may be compromised. (MM)	Conduct of Operations
	...With observation alone, which represents the first and shallowest layer of knowledge acquisition, the operator is unable to surpass a certain cognitive level necessary for the retention of knowledge. Consequently, there is a lack of clarity on **how to operate the system**, impacting the way they will **conduct future plant operations**. (TM)	
	Without up-to-date and organized information to obtain insights into the functioning of the unit's systems, one cannot speak of process safety. The absence of information leads to **a lack of knowledge**, impacting all elements reliant on this knowledge for effectively managing risks. (MM)	Process Knowledge Management
	If information collection has been compromised, professionals from Company B lack the complete operational history and necessary procedures. It's akin to operating an old asset without the accumulated learning from years of experience. Consequently, the new operator's **ability to analyze risks** or make decisions based on facts and data has been entirely lost. (MM)	Hazard Identification and Risk Analysis
	The absence of data and information for process safety is critical and can perpetuate this problem for an extended period. Company B may subsequently conduct **a risk analysis with incorrect or incomplete information**, potentially relying on non-existent layers of protection. There is a risk of underestimating an accidental scenario by considering an implemented recommendation that has not been put in place..(TM)	

[1] TM - top manager; MM - middle manager

Source: The author, 2024

Additionally, based on the interviews, not all challenges were found to have the same level of impact to process safety. Challenges associated with IKT elements 1 (contractual characteristics), 2 (decision-making characteristics), 4 (transfer period), 7 (availability), 8 (proactivity), 9 (provision of resources), and 19 (access to databases) were considered by the experts as most critical because they are difficult to solve during the transition through corporate governance mechanisms. If knowledge is not transferred due to these challenges, future operational deviations may not be mitigable, potentially leading to process safety incidents. On the other hand, challenges associated with IKT elements 6 (degree of similarity), 12 (identification of training needs), 14 (transfer objectives), 15 (transfer scope), 18 (definition of routines), and 20 (mechanisms used for knowledge transfer) were considered less critical. These elements could be managed during the transition if there was a strong governance established through the most critical IKT elements. Mitigative measures could be taken through governance processes or through the experience of the professionals involved.

Moreover, not all challenges presented to the experts were found to be associated with process safety issues. Some were classified as facilitators or hindrances to knowledge transfer, such as IKT elements 5 (alignment of the two companies in all working environments), 10 (previous experiences), 11 (lessons learned), and 22 (due diligence). Others were seen as derivatives of primary challenges, such as IKT elements 3 (conflict resolution), 13 (training effectiveness) and 21 (collaboration duration). In these cases, focus was given to the primary challenges.

The experts unanimously identified the RBPS element of Process Knowledge Management as being weakened by the failure in IKT. This element is inherently related to knowledge, as it includes both information collection activities, as well as interpretation and understanding of data by professionals. Other impacted elements of the RBPS framework depended on the type of IKT challenge.

In general, the experts found that IKT challenges hampered knowledge transfer in three ways: data sharing, personnel interaction, and facility access. For instance, challenges in contractual characteristics (element 1) were found to have effects on all three aspects, with broad impacts on process safety. Because the contract did not specify the content of the transfer, certain data was not shared. Depending on the type of data, such as an emergency response procedure, this could then have significant safety implications, specifically Emergency Management in this case. Since the contract did not establish clear objectives for personnel interaction, Workforce Involvement was hindered. Due to an insufficient number of staff from Company B was defined in the contract to access the facility, they were not able to learn all the details of that facility which are required to operate it safely, thereby impeding the Compliance with Standards.

Challenges in decision-making characteristics (element 2), especially unilateral decision making, were found to reduce personnel interaction between both companies and impact Company B's understanding of the facility's processes, which is essential to Hazard Identification and Risk Analysis.

The unpredictability of the transfer period (element 4) caused frustration among the personnel of both companies, leading to friction in their interactions and reducing synergistic exchanges. Such exchanges were also made more difficult by the inability to resolve differences (element 6). With minimal interaction, tacit knowledge can hardly be shared (Sudhindra; Ganesh; Arshinder, 2017) which is crucial to understanding the current operation of the facility, i.e., Operating Procedures, and the state of the assets, i.e., Asset Integrity and Reliability.

At a basic level, the insufficient access to data (element 19) eroded the foundation of knowledge about the facility for Company B, impacting Process Knowledge Management. Furthermore, the lack of human resources (element 9), as well as available (element 7) and proactive (element 8) personnel, led to the low prioritization of IKT. By not pursuing excellence in the IKT, process safety was debilitated in the Conduct of Operations, Workforce Involvement and Management of Change.

Overall, the impacts to workforce involvement and compliance with standards compromised the earliest RBPS pillar, Commit to Process Safety. Following the low commitment, breakdowns in knowledge management and hazard identification negatively impacted the RBPS second pillar, namely Understand Hazards and Risks. During and after the asset transition, impacts to the development and implementation of operational procedures, emergency responses, asset integrity management, and workforce performance, compromised the third RBPS pillar, Manage Risk. Thus, the majority of RBPS pillars were affected, making Platform X process more vulnerable to accidents, as the ability to respond to accidents was diminished.

4.5 Discussion

Despite operating other offshore assets, personnel from the buying company are inherently unfamiliar with the specificities of the field and the facility and their implications on operations. The transfer needs to be carefully conducted, based on a well-structured governance framework, to avoid resistance from both companies' personnel in transmitting and absorbing knowledge and to facilitate the unrestricted transfer of data and information, which are essential for safely operating an ageing asset in the future.

If people are not available for the transfer (either because they were not hired in advance of the transition or because they are not engaged or resistant to the process), knowledge transfer is compromised (Kang; Kim, 2017) and tacit knowledge is lost (Sudhindra; Ganesh; Arshinder, 2017). For an ageing facility or asset, as the case presented herein, the overreliance on explicit knowledge gathered through reading of technical documents and procedures is especially problematic. This is because explicit knowledge will largely reflect the plant's initial state, i.e., "as good as new," creating a gap between the assumed and actual state. This gap leaves the buyer unprepared to safely operate a mature asset.

Knowledge gaps (both tacit and explicit) introduce uncertainties in facility operations, making it challenging or even unfeasible (depending on the size and type of gap) to identify hazards and analyze risks. This in turn makes it difficult to manage facility risks, which could lead to process safety incidents (i.e. loss of containment). While personnel from the buyer could potentially learn "from the asset itself" starting from Day 1, operation through trial and error can lead to safety incidents. This approach is characterised by an unawareness of the background of the facility (degradation, performance, construction, maintenance) and brings vulnerabilities. By “experimenting with the facility”, the buyer could make suboptimal decisions that would have been clearly misguided to the seller. Furthermore, operating under unexpected situations becomes the new status quo; operations are less fluid. In such cases, professionals expend more energy in managing operations, becoming more stressed and fatigued, which can hinder their ability to respond effectively to unexpected or emergency situations.

Good governance during the IKT is key to addressing underlying knowledge management issues and formalizing essential elements for effective IKT (Kang; Kim, 2017), such as clear objectives and scope, routines between the parties, appropriate mechanisms, time allocation for the transfer, dedication of professionals, decision-making and conflict resolution mechanisms, among others. Additionally, it can identify the need for corrective actions to redefine strategies during the transfer if necessary. From the perspective of process safety, “Management of Change” is one of the elements of the RBPS Manage Risk pillar, that addresses the implications to process safety of all types of change, such as in equipment, technologies, and personnel. Since operators are already aware how to apply the Management of Change, it could have been used to address the change in operations due to facility acquisition as well. Therefore, all the stages of planning and implementing the IKT, using information from the due diligence, could have been structured by this element. This information could include plant diagnosis, as well as the main differences and gaps between the two companies, enabling a better understanding of hazards and risks.

Improving the IKT planning and applying the Management of Change will likely reduce the loss of relevant information and data needed for future operations, while also ensuring clarity for professionals from both organizations. Formalizing this planning into a written IKT procedure is suggested, as those implementing it may be unfamiliar with the IKT activities. Thus, training in the procedures is required. Furthermore, the mechanisms for IKT do not need to match those used in regular operations. For instance, complementary IKT methods can be defined based on the tacit nature of knowledge being shared, function type, and professionals' preferred learning styles. This could involve workshops, theoretical classes, virtual reality simulators or 3D unit simulations, joint reading of technical documents, etc. in addition to shadowing. Similarly, performance assurance mechanisms could be collaboratively designed to leverage company A's expertise. Their professionals could support evaluating and mentoring company B's learning.

4.6 Conclusion

This study explores the differences in IKT challenges across operating environments and uncovers the impacts of these challenges on process safety. The study shows that, while many of the challenges are similar in the onshore and offshore environments, they stem from unique underlying root causes that are specific to each environment. Furthermore, certain challenges are unique to the onshore environment, such as those related to contractual characteristics and due diligence. Based on the identified challenges in both environments, the study shows a clear connection between the failure in IKT and certain pillars and elements of Risk-Based Process Safety (RBPS). The main impacted RBPS element is Process Knowledge Management, which is under the pillar Understand hazard and risk. Other impacted elements include Hazard Identification and Risk Analysis; Conduct of Operations; and Asset Integrity and Reliability. The study was also able to differentiate the IKT elements according to their impact on process safety, classifying the elements into 4 categories: (1) Most critical (e.g. contractual characteristics, decision making characteristics); (2) Less critical (e.g. degree of similarity, identification of training needs); (3) Facilitators or hinderers of knowledge transfer (e.g. alignment of the two companies in all working environments, and previous experience); and (4) Offshoots of other challenges (e.g.).e.g. conflict resolution and training effectiveness).

Thus, the study contributes to the IKT body of knowledge by distinguishing the IKT elements according to their criticality for process safety and identifying the most critical, which should be the focus of the company acquiring the asset. It also highlights the need to consider IKT in different work environments, beyond the company level considered by previous studies. Work environments should, thus, be included as new antecedent factors in IKT frameworks. Furthermore, the study contributes to the process safety literature, by identifying the process safety pillars and elements that are impacted by a failure in IKT during asset acquisition with no personnel transfer. Moreover, for the literature on life extension, the study reinforces the importance of including knowledge transfer as part of the organizational issues considered in the decision-making process of asset life extension, even though the literature is still predominantly oriented towards material degradation.

The transfer of an asset, especially one that is reaching the end of its useful life, requires specific behaviors from the involved companies. A shared commitment and responsibility to safety is essential to process safety in the context of oil and gas platforms and becomes even more important during and around a facility transfer period. To make this commitment clear, the facility transfer contract should specifically state that the transfer refers not only to the physical asset, in this case the facility, but also the data, as well as tacit and explicit knowledge. If this is not clear, the scope of the transfer can be left to subjective interpretation, and IKT may not occur.

Furthermore, personnel should be involved from the beginning in preparing for the transfer. Seller company professionals should be engaged early on to organize the data, prepare training, and overall take ownership of the IKT process. This ensures that the transition is perceived as a partnership rather than a competition between the two companies, where all information is deemed proprietary, and collaboration is misperceived. If seller company professionals are not engaged in the transfer, further pillars of process safety can be compromised and ultimately, can cause process safety incidents, compromising the safe operation of the platform in the future.

While the case of asset acquisition presented herein, with no transfer of personnel, may be extreme, it is common and depicts an acute case of IKT failure, highlighting the risks associated with asset acquisition and the need for further research in developing a regulatory scheme, that could reduce the risks of accidents of large magnitude on offshore operations. It should be noted that the findings described herein are based on one case study and the presentation of related summarized challenges to process safety experts. This procedure is not free from cognitive biases and the “Availability heuristic” may have impacted the selection of data and consequently the responses. Additionally, the presentation of the challenges is naturally subject to the “framing effect”, thereby influencing how interviewees understood data and acted on it.

5. INTRODUCTION OF A CARBON FOOTPRINT ASSESSMENT IN THE OIL AND GAS FACILITY LIFE EXTENSION DECISION-MAKING PROCESS

In large oil and gas producing countries, extraction and processing activities, including upstream activities, can represent a large share of domestic emissions. As oil fields approach their expected service life and reach depletion, energy use and GHG emissions increase per unit of produced oil, shifting operations away from their optimal point. Thus, it is paramount that oil field life extension decisions account for energy use and GHG emissions. However, many facilities are having their service life extended without considering this energy inefficiency and previous life extension decision making studies have neglected GHG emissions. Addressing this issue, this paper proposes the inclusion of a carbon footprint assessment within the evaluation of oil and gas offshore production facility life extension. The carbon footprint assessment adds an environmental lens to the evaluation of ageing, formerly evaluated according to material degradation, obsolescence and organizational issues. An eleven-stage framework is proposed to systematize the ageing related carbon footprint assessment and support life extension decision-making: (1) Objective definition, (2) Scope definition, (3) Field conditions description, (4) Scope breakdown into manageable portions, (5) Detailed data collection for each process and subsystem, (6) Input and output definition for each process and subsystem, (7) Process modeling, (8) Methodology definition for energy demand and inefficiency estimate, (9) Monitoring indicator definition, (10) Performance evaluation, and (11) Interpretation of results. The proposed framework is applied to a hypothetical case study, developed with data from a typical oil and gas offshore production platform operated in Brazil. Two LE improvement strategies were simulated, i.e. reducing the number of gas turbines, and increasing the export of natural gas. Both alter the modus operandi of the compression system and do not require additional equipment installation. These strategies resulted in a combined reduction of 922,000 t CO_2 during the extended 10-year operation. This outcome demonstrates that by applying the framework opportunities for reducing energy use and GHG emissions during life extension can be identified and quantified, facilitating life extension decision-making.

5.1 Introduction

In the oil and gas industry, around 3 to 4% of the energy generated is used by the industry itself for extraction and processing (Masnadi; Brandt, 2017a). Furthermore, 50% of this energy consumption is upstream, i.e. well-to-refinery operations (Masnadi *et al.*, 2018a), and leads to significant greenhouse-gas (GHG) emissions. Member companies of the International Association of Oil and Gas Producers (IOGP) consumed 1.4 gigajoules of energy and flared 8.0 tonnes of gas for every tonne of hydrocarbon produced in 2020. These members are 60 operating companies in 70 countries, which represent around 30% of 2020 global production sales (IOGP, 2021).

From a life-cycle perspective, GHG emissions from fossil fuel use are still more important downstream, as they represent 90% of all oil and gas emissions. Nevertheless, in large oil and gas producing countries, extraction and processing activities can represent a large share of domestic emissions. For instance, in Russia, Norway and Canada these emissions represent more than 20% of total national emissions (Masnadi; Brandt, 2017a; Brandt *et al.*, 2018; Farajzadeh, *et al.*, 2022). Examples of GHG intensive activities for crude extraction include pumping (for hydrocarbon extraction, water injection, and oil and gas transmission), compression (for gas reinjection in enhanced oil recovery, and oil and gas transmission), heating (of output fluid streams to separate oil, gas, and water), steam production, and electricity generation through turbines (Coulomb; Henriet; Reitzmann, 2021).

As more oil fields deplete and operated for longer durations, energy efficiency declines, leading to greater energy consumption and emissions per unit of fuel extracted (Coulomb; Henriet; Reitzmann, 2021). Gallagher (2017) noted that while oil production decreases with time in a given oilfield, GHG emissions approximately double over a 25-year period. Certain sites even had a tenfold increase in emissions. This trend does not depend on the type of crude oil (Masnadi; Brandt, 2017a), but varies over time. Thus, oil field carbon intensity is likely to be higher during the period extended beyond its useful life. Not only is the carbon footprint of upstream units undergoing life extension (LE) important, there is also increasing pressure for the oil and gas industry to reduce emissions, potentially by improving energy efficiency and increasing the use of renewable energy sources (Masnadi, *et al.*, 2018b). Beyond higher GHG emissions, LE can also bring many other challenges. While previous GHG emissions studies have considered GHG emissions of oil and gas assets at end of life, they have not analysed LE scenarios, nor explored how to include this within the broader LE decision-making process. On the other hand, LE decision-making studies have neglected GHG emissions (PSA, 2005; Hornlund *et al.*, 2011; Ersdal; Sharp; Galbraith, 2014; Ferreira *et al.*, 2020).

Furthermore, the comprehensive review conducted by Shafiee *et al.* (2019) on decision-making support (DMS) methods within the literature, aimed at aiding stakeholders in the upstream oil and gas industry, highlighted a significant gap in addressing the prevailing challenges of life extension. Despite the life extension being a key challenge in the sector, over the past four decades, the review emphasized a dearth of research studies utilizing DMS methods to specifically address the intricate issues associated with extending the operational life of assets.

Accordingly, the objectives of the present paper are as follows: (1) to propose the inclusion of GHG emission assessment for the LE decision making process; (2) to develop a framework for assessing GHG emissions as part of a broader service life extension decision framework; (3) to validate the methodology through a case study.

The paper is divided into five sections. The first section, the introduction, presents a rationale for focusing on oil and gas field GHG emissions, particularly during service life extension. Section 5.2 reviews previous literature on oil and gas field service life extension. It is shown that previous researches have been centered on technical and organizational issues, largely ignoring operational environmental impacts. This section also summarizes the key characteristics of assets whose service life is extended and highlights the importance of evaluating asset GHG emissions. Section 5.3 describes the proposed methodology for evaluating GHG emissions as an additional attribute of systems that should be accounted for during service life extension decision-making. Section 5.4 validates the proposed framework on a hypothetical case study based on real production units. This example demonstrates how mitigation strategies might be integrated in a Life Extension Management Plan. Lastly, section 5.5, presents overall conclusions.

5.2 Theoretical Background

This section presents a review of available literature regarding oil and gas field service LE, the key characteristics of fields during their period of LE and a summary about previous papers focused on offshore oil and gas asset GHG emissions and energy consumption assessment. This review reveals a gap in the literature, as well as in regulations, highlighting the need to include GHG emissions in analysing asset ageing.

5.2.1 Factors Influencing LE Decision-Making

Asset ageing in the oil and gas industry has been classified into four types (Ersdal; Sharp; Galbraith, 2014): functional (physical damage), technological (obsolescence of standards and regulations), organizational (personnel ageing and resource limitations), and knowledge-based (outdated or unavailable asset documentation). In contrast, Hokstad *et al.* (2010) considered knowledge related ageing to be part of organizational issues, and further broke down each ageing type into multiple factors. For example, degradation may be caused by three key factors: material properties, operating conditions, and environmental conditions.

As an asset ages and approaches the end of its useful life, it becomes imperative to validate that it can still be operated safely through the LE decision-making process. While Ferreira *et al.* (2020) applied the same ageing classification presented by Hokstad *et al.* (2010) and proposed a guideline for LE management, none of these studies addressed GHG emissions within the asset ageing context. Environmental impacts during extended asset life are considered in these studies indirectly in the evaluation of material degradation of a given system, subsystem or component (SSC). In this assessment the risk of loss of containment is calculated considering the impact on the environment, in addition to people, image and property. However, this evaluation does not consider the effect of GHG emissions on the environment.

The assessment of oil and gas asset GHG emissions, energy efficiency, and overall environmental impacts has been motivated by societal demand, emerging risks from regulatory changes, and the potential for operating cost reduction (Baron; Fischer, 2015). Recent years have seen stricter GHG emission regulations in the oil industry worldwide. For instance, Canada and Brazil have set restrictions on production levels and penalties tied to excessive flaring (C-NLOPB, 2017; ANP, 2020). Other countries, including Norway, Sweden, France, Portugal, and Japan, have imposed taxes on CO_2 and NOx emissions (World Bank Group, 2023). Despite the rising financial risks posed by these regulations, GHG emissions have not yet been considered in LE studies, which have primarily focused on the technical, operational, and organizational attributes of systems and companies. This points to a gap in the literature and an opportunity to incorporate GHG emissions into LE management.

5.2.2 Asset Characteristics During LE

As the intensity of GHG emissions escalates over time in oil and gas production, a thorough understanding of ageing assets is crucial for effective estimation and management of these emissions during LE. A myriad of factors including material properties of the assets, technologies used, operating conditions, environmental conditions, and personnel competence contribute to GHG intensity. Furthermore, many of these factors are dynamic, thereby complicating their management. For example, oil field reservoir properties and composition vary over its lifetime (Voldsund *et al.*, 2014; Yehia, *et al*, 2023). Oilfield assets being considered for LE generally have ages between 20 and 25 years. These assets operate under deteriorated conditions and process fluids with distinct characteristics from those during installation. Their reservoirs are also likely nearing depletion, leading to additional operational challenges. Production streams in aged oilfields consist largely of water and a small oil fraction (Masnadi; Brandt, 2017b). Over time, the natural pressure in the reservoir decreases as oil and gas are extracted, and the remaining pressure is no longer sufficient to produce the fluids (Devold, 2013; Farajzadeh, 2019; Farajzadeh, *et al.*, 2022). These characteristics have the following operational consequences:

(i) increased water and/ or gas by-products (Masnadi; Brandt, 2017a; Rocher; Garnaud, 2017);

(ii) increased mass and volume of fluid lifted and processed per unit of oil produced (El-Houjeiri; Brandt; Duffy, 2013; Masnadi; Brandt, 2017A; Gallagher, 2017; Masnadi *et al.*, 2018a; Coulomb; Henriet; Reitzmann, 2021);

(iii) higher pumping requirements to lift the additional fluids (Farajzadeh, 2019); and

(iv) need for more energy-intensive enhanced oil recovery (EOR) techniques, such as water or gas injection, to compensate for reduced natural pressures (Masnadi; Brandt, 2017b; Coulomb; Henriet; Reitzmann, 2021; Vafi; Brandt, 2014; Farajzadeh, *et al.*, 2021).

In addition to increased energy requirements, the energy efficiency of the equipment itself should also be considered. Equipment and offshore platforms are generally designed to handle peak oil and gas production rates (Rocher; Garnaud, 2017; Nguyen *et al.*, 2014). However, these rates vary over time, as water volumes increase, and fluid temperature and pressures fluctuate. Consequently, the efficiency of generators, compressors, and pumps diminishes. These assets also deteriorate as they age, further impacting their energy efficiency. Additionally, technologies have advanced over the years, and newer models are more efficient and less carbon intensive. Extra emissions are also caused by changes in venting, flaring and fugitive (VFF) emissions (Masnadi, *et al.*, 2018a; El-Houjeiri; Brandt; Duffy, 2013; Sedlar *et al.*, 2018).

Because of this combination of increasing challenges in environmental, operational and asset conditions as oil fields and facilities age, it is expected that emissions per unit of produced oil increase. Furthermore, these conditions are dependent. They can create negative feedback loops, augmenting impacts on energy use and emissions. For example, the depletion of oil causes lower pressures and fluid availability, which require additional pumping. This additional pumping is not what the equipment was designed for and is thus more inefficient. Inefficient operation of equipment causes faster asset deterioration.

5.2.3 GHG Emission assessment

To support the development of a framework for assessing GHG emissions as part of a broader LE decision, previous papers that focused on offshore oil and gas asset GHG emissions and energy consumption assessment were reviewed. The scope of this literature review was refined according to the following factors:

- No studies on GHG emission assessments for offshore oil and gas facility end-of-life decision-making were found. Nevertheless, studies that investigated carbon footprint issues in oil fields approaching their end-life were reviewed.
- Only studies related to upstream impacts of offshore oil and gas production were included, to match the focus of the present paper. Therefore, papers evaluating onshore production, non-conventional production, and drilling as well as midstream and downstream impacts were not reviewed.
- All key findings and mitigation strategies summarized from the papers are of a technical nature, not regulatory. Regulatory measures were not included in the review.

A summary of all the reviewed studies is presented in Table A.3 (supplementary material), confirming that carbon footprint assessment is a well-established and widely explored topic in the literature. The focus of the review herein is on their methodological approach to evaluation, revealing a broad variety in (i) assessment methodology, (ii) level of detail and scope, and (iii) presentation of results, among other aspects.

The assessment methodology most often applied by previous studies is a top-down macroscale economic data-based approach, due to the complexity of developing integrated life-cycle models (Masnadi, *et al.*, 2018a). However, economic accounting models provide an incomplete and rough assessment of impacts and cannot explain the underlying physical drivers of energy consumption and emissions from oil and gas fields (Vafi; Brandt, 2014). A more granular, engineering-based bottom-up model addresses the lack of physical insight from the top-down approach. Bottom-up life-cycle assessment (LCA), developed with engineering-based models, emerged as a solution for modeling energy consumption and crude oil emissions from important segments of the energy sector (El-Houjeiri; Brandt; Duffy, 2013). However, these models are data-intensive, requiring multiple inputs often not readily accessible in public literature (Masnadi *et al.*, 2018a).

The crude-oil-specific engineering-based LCA or process-based LCA models estimate crude oil emissions by modeling specific subprocesses within the oil production and processing stage (e.g., crude oil lifting or gas compression). This specificity allows improved estimates of GHG emissions of oil production, as long as underlying data is available (Vafi; Brandt, 2014). Table A.3 (supplementary material) presents several examples of carbon footprint assessment using bottom-up LCA (Nguyen, et al, 2016; Farajzadeh, 2019; Farajzadeh, *et al.*, 2021). Other studies presented less comprehensive carbon footprint analyses, not covering the entire process chain (Oliveira; Van Hombeeck, 1997; Nguyen *et al.*, 2014; Pierobon *et al.*, 2014; Gallo *et al.*, 2017; Riboldi; Nord, 2017).

In terms of level of detail and scope of the analysis, some studies based their evaluation on general data, considering field information but no specific plant parameters (Brandt, 2011; El-Houjeiri; Brandt; Duffy, 2013; Masnadi *et al.*, 2018a; Masnadi *et al.*, 2018b; Farajzadeh *et al.*, 2022). Others accounted for facility specificities (Nguyen *et al.*, 2014; Pierobon *et al.*, 2014; Farajzadeh, 2019), either relying on time-averaged data (Rocher; Garnaud, 2017; Farajzadeh, *et al.*, 2021), operational-specific day (Voldsund *et al.*, 2014; Nguyen, et al, 2016), or qualitative information like expert opinions on equipment or system performance (Rocher; Garnaud, 2017). Furthermore, studies may cover various plant systems (Voldsund *et al.*, 2014; Nguyen, et al, 2016; Rocher; Garnaud, 2017) or focus on a particular system. For instance, the authors Gallagher (2017), Farajzadeh *et al.* (2021), Oliveira and Van Hombeeck (1997), Pierobon *et al.* (2014) and Gallo *et al.* (2017) developed specific assessments for water injection process, separation process, enhanced oil recovery, waste heat recovery and compression systems.

While some studies focus only on the production plant (Oliveira; Van Hombeeck, 1997; Gallo *et al.*, 2017; Farajzadeh, *et al.*, 2021), others included the interface between the process plant and utilities plant (Voldsund *et al.*, 2014; Nguyen, et al, 2016; Rocher; Garnaud, 2017; Riboldi; Nord, 2017). Additionally, some assessments evaluated installation performance over time, comparing different life stages, (e.g. start-life, plateau and end-life) (Nguyen *et al.*, 2014; Farajzadeh, *et al.*, 2022). In this case, carbon emission levels are presented according to varying temporal estimates of the production curve, water-oil ratio (WOR), gas-oil ratio (GOR) and different operating strategies.

Regarding presentation of results, several studies used exergy analyses to pinpoint the locations of maximal thermodynamic losses. The exergy analysis identifies the location and scale of inefficiencies, and can be used to compare alternative scenarios and optimize processes (Oliveira; Van Hombeeck, 1997; Bierman *et al.*, 2014; Nguyen, et al, 2016). The exergy analysis can also be combined with a LCA (Nguyen, et al, 2016; Farajzadeh, 2019; Farajzadeh, *et al.*, 2021). While some studies used these results to qualitatively reflect on asset strategies (Nguyen *et al.*, 2014; Masnadi, *et al.*, 2018a; Farajzadeh, 2019; Farajzadeh, *et al.*, 2021; Farajzadeh, *et al.*, 2022), others presented specific quantitative proposals for reducing emissions (Voldsund *et al.*, 2014; Nguyen et al, 2016; Gallo *et al.*, 2017; Riboldi; Nord, 2017). Certain studies also included an economic evaluation, in addition to the environmental perspective, to holistically optimize the performance of the unit (Nguyen, et al, 2016; Nguyen *et al.*, 2014; Pierobon *et al.*, 2014). However, these economic evaluations are still related to the environmental perspective of regular operations, and do not consider all costs which would be incurred in a LE scenario, nor the restricted time for the LE period.

Thus, based on these studies (more details in Table A.3), there is a significant variability in previous carbon emission assessments. Moreover, it was observed that certain systems or processes are generally most relevant from a thermodynamic and emissions perspective, namely compression system, EOR techniques, heating and cooling system, power generation and production manifold (detailed description in the first column of Table A.4). Although these studies offer a comprehensive assessment of the carbon footprint of oil and gas assets from installation to end-of-life, they do not explore the issue of facility life extension and its unique characteristics. These gaps are addressed by this article through the framework proposed in section 5.3 below.

5.3 Proposed Framework

The LE of oil and gas facilities allows companies to operate on mature fields. However, this shift towards aged assets should consider the characteristics of such assets, and the challenges they face, especially considering increased energy requirements and emissions, as described in Section 5.2. Companies should mitigate negative environmental impacts through more energy-efficient extraction and reduced emission intensity. Accordingly, this study proposes a framework for evaluating GHG emissions as part of LE management. This study extends upon the framework developed by Ferreira et. al (2020), by including a GHG emission assessment in the technical evaluation of the asset whose life may be extended. This analysis is added in parallel to the existing evaluations of material degradation (Ferreira *et al.* 2020), obsolescence (Ferreira *et al.*, 2023) and organizational issues (Ferreira *et al.*, 2024). This way GHG emissions are assessed early in the LE decision process, to account for LE motivation, LE period and asset condition ratings. The proposed framework for carbon footprint evaluation is presented in Section 5.3.1, and the subsequent definition of the LE strategy is described in Section 5.3.2. Subsequent stages of the decision-making process are provided in the framework developed by Ferreira et. al (2020), including Assessment of Economic Issues and Definition of LE Management Plan. These are outside the scope of this paper because they need to consider all aspects covered by the technical evaluations (GHG emissions, as well as material degradation, obsolescence, and organizational issues).

5.3.1 <u>Evaluation of carbon footprint</u>

The assessment of GHG emissions is generally centered on reducing GHG emissions and energy costs while maintaining field productivity (Margarone et. al, 2011). This is achieved by optimizing energetically expensive processes (Farajzadeh, 2019), designing alternative systems/facilities/concepts, adjusting process parameters (Farajzadeh, 2019) and/or plant configurations (Sutoyo *et al.*, 2023; Sedlar *et al.*, 2018). It is important to note that energy use can be easily converted to emissions based on the GHG intensities of specific energy sources. Previous studies on carbon emission assessments have had various purposes and specificities, as discussed in section 5.2.3.

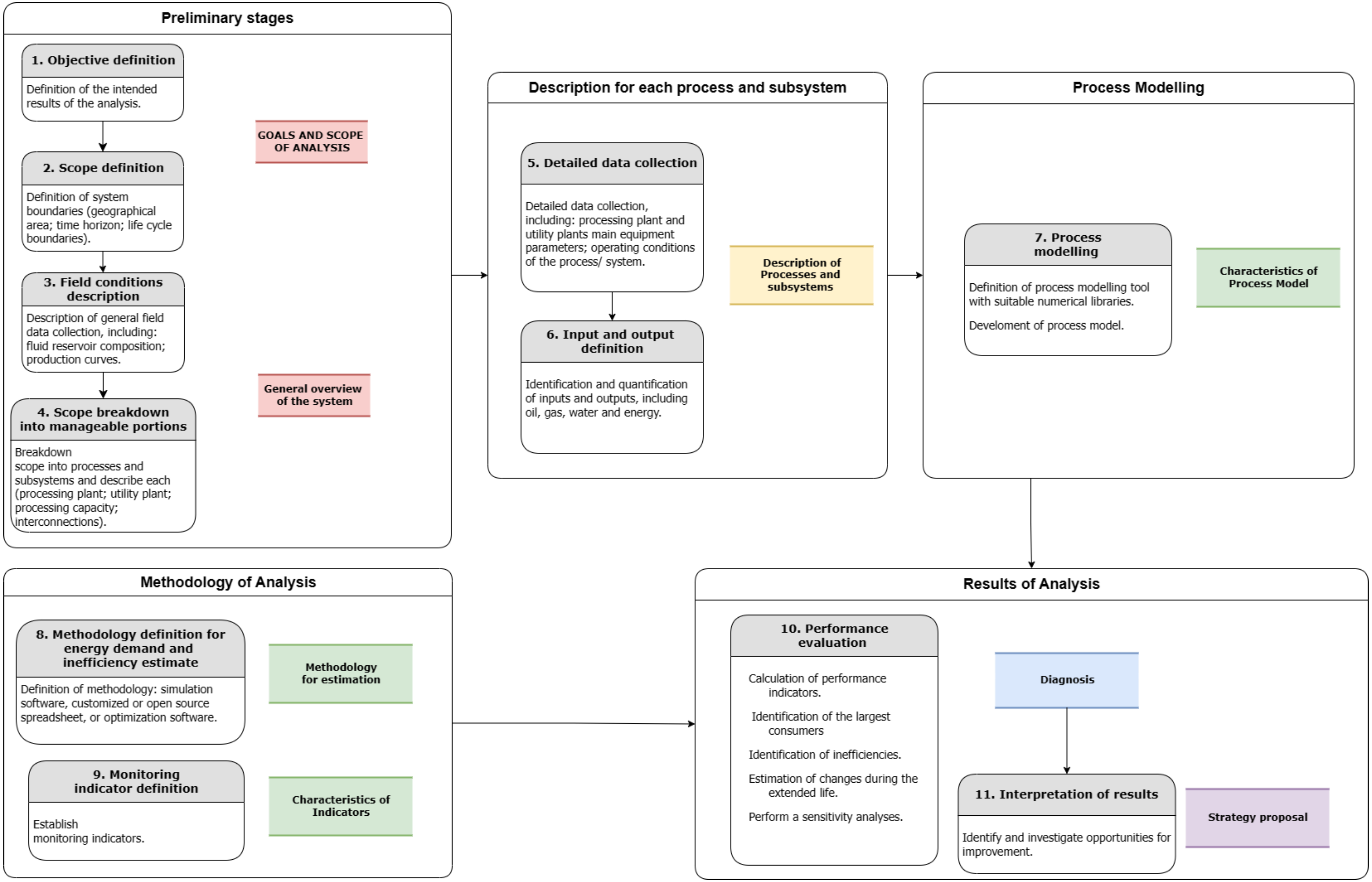
Based on this literature and considering the context of LE, a GHG emission assessment framework is proposed in Figure 5.1 and described in Table 5.1. The framework establishes 5 macro-activities: Preliminary stages, Description for each process and subsystem, Process modeling, Methodology of analysis and Results of analysis.

Preliminary stages comprise activities for preparing the evaluation and establishing a general overview of the system, including objective definition (stage 1), scope definition (stage 2), description of field conditions (stage 3) and scope breakdown into manageable portions (stage 4). Once these stages are complete, it is possible to describe the process and subsystem and define the analysis methodology.

The Description for each the process and subsystem encompasses detailed data collection (stage 5) and input and output definition (stage 6), guaranteeing that all required details of the processes and subsystems are included in the analysis. Based on this description, the Process modelling can be conducted, defining the thermodynamic modelling (stage 7). In parallel, the Methodology of analysis encompasses methodology definition for energy demand and inefficiency estimate (stage 8) and monitoring indicator definition (stage 9), establishing how the performance indicators will be defined and estimated.

Given the outputs of all these stages, the Results of analysis provide a diagnostic of the process through the performance evaluation (stage 10), and proposes strategies to mitigate identified inefficiencies, based on the interpretation of results (stage 11).

Figure 5.1 - Framework for evaluation of carbon footprint



Source: The author, 2024

Table 5.1 - Description of the stages of proposed framework

	#	Stage	Results of the stage
Preliminary stages	GOALS AND SCOPE OF ANALYSIS		
	1	Objective definition	Explicit definition of the intended results of the analysis.
	2	Scope definition	Definition of system boundaries according to: a. geographical area– plant and process/ system included in the analysis; b. time horizon – field service life as set by the request for LE; c. lifecycle boundaries – selection of lifecycle stages included in the analysis, e.g. installation, extraction, raw material processing, transportation, and waste management.
	GENERAL OVERVIEW OF THE SYSTEM		
	3	Field condition description	Description of general field data collection, including: a. Fluid reservoir composition (ex. petroleum composition; GOR; WOR); b. Production curves, highlighting oil and gas production decline and intended LE.
	4	Scope breakdown into manageable portions	Breakdown scope into processes and subsystems, and describe each according to the following characteristics: a. Processing plant and utility plant configuration (e.g. production manifold, separation trains, oil treatment process, export process, condensate stabilisation system, produced water treatment process, gas recompression train, gas compression and treatment process, carbon dioxide compression process; fuel gas system, gas turbines, waste heat recovery process). b. Processing capacity (e.g. oil treatment section, vapour recovery unit, gas compression section). c. Interconnections (P&ID) between equipment and processing and utility plant.
Description for each process and subsystem	DESCRIPTION OF PROCESSES AND SUBSYSTEMS		
	5	Detailed data collection	Detailed data collection, including: a. Processing plant and utility plants main equipment parameters (e.g. quantitative, size, efficiency, load factor). b. Operating conditions of the process/ system (e.g. pressure, temperature, mass flow, fluid composition)
	6	Input and output definition	Identification and quantification of inputs and outputs, including oil, gas, water, energy and/ or chemical components.
Process modelling	CHARACTERISTICS OF PROCESS MODEL		
	7	Process modelling	Selection of process modelling tool with suitable numerical libraries. Development of process model.
Methodology of analysis	METHODOLOGY FOR ESTIMATION		
	8	Methodology selection for energy demand and inefficiency estimate	Selection of methodology for energy and inefficiency estimation: ready-made or customized (i) simulation software/tool, (ii) spreadsheet, or (iii) optimization software. OBS: The choice of methodology will depend on the granularity of the available data/information, the complexity of the system under evaluation, and the tools at hand.
	CHARACTERISTICS OF INDICATORS		
	9	Monitoring indicator selection	Establish monitoring indicators (e.g. power consumption, power and heat use, exergy demand, thermal and exergy efficiencies).

Results of analysis	DIAGNOSIS		
	10	Performance evaluation	For each process and subsystem: a. Calculation of performance indicators b. Identification of the largest consumers (energy-intensive process) c. Identification of inefficiencies (equipment level) Perform a sensitivity analysis, considering equipment parameters, operating conditions, inputs and outputs for each process and subsystem during the extended life.
	STRATEGY PROPOSAL		
	11	Interpretation of results	Identify and investigate opportunities for improvement.

Source: The author, 2024

5.3.1.1 Definition of strategy

Based on the results of the evaluation of carbon footprint (item 5.3.1), a strategy for emission reduction should be defined for the asset. This strategy should observe space and weight limitations of the platform and assume that a reduced equipment inventory is preferable, due to risk management issues onboard. According to the Climate Change Questionnaire of the Carbon Disclosure Project (CDP), the most common strategies for emission reduction in 2021 were oil/natural gas methane leak capture/prevention and process optimization (Sedlar *et al.*, 2018; CDP DISCLOSURE INSIGHT ACTION, 2021). Furthermore, 80% of all reported strategies had a payback period of less than ten years. This suggests that for platforms contemplating a LE, usually for 5 to 10 years, most of these initiatives could be financially viable.

Masnadi *et al.* (2018b) propose three types of strategies to decrease GHG impacts: resource management, resource prioritization, and innovative technologies. <u>Resource management</u> comprises strategies for reducing energy use and increasing energy efficiency, such as the following: (i) increasing efficiency of energy-intensive processes, e.g. by reducing the energy demands of the processing plant (e.g. power and heating) or increasing the efficiency of the energy conversion processes (e.g. gas turbines and cogeneration) (Nguyen, et al, 2016); (ii) integrating systems to recover energy from production manifolds or product flows (Nguyen, et al, 2016); (iii) upgrading energy conversion processes, e.g., by turning gas turbines and furnaces into cogeneration plants, or replacing them with smaller, more efficient ones (Nguyen, et al, 2016); (iv) increasing the efficiency of specific equipment for marginal improvements (Farajzadeh, *et al.*, 2022; Sutoyo *et al.*, 2023); (v) utilizing energy losses on the platform for overall system efficiency (Farajzadeh, *et al.*, 2022); and (vi) reducing the volume of injected fluids (Farajzadeh, *et al.*, 2022).

<u>Resource prioritization</u> is related to the use of alternate sources of energy, such as using electricity generated from onshore renewable sources (Pöyri, 2011), electrifying offshore platforms (Nguyen, et al, 2016), and using offshore wind farms (Korpås; Warland; Tande, 2012; Riboldi; Nord, 2017;). The latter avoid the need for long and expensive connections to shore and may be configured to share the load with gas turbines or to allow one of the gas turbines to shut down. Lastly, <u>innovative technologies</u> can be implemented to change the modus operandi of a unit. For example, if production systems are shifted to subsea, offshore production units can be reduced. The implementation of subsea separation and injection systems, such as in the Gulf of

Mexico, West Africa, Brazil and North Sea can drastically reduce the demand for energy in the production phase of the units and, consequently, emissions (Euphemio *et al.*, 2007; Euphemio; Kuchpil; Figueiredo, 2009; Euphemio *et al.*, 2012; Siqueira *et al.* 2012; Moraes *et al.*, 2012; Orlowski *et al.*, 2012; Pereira *et al.*, 2012). The subsea system avoids the need to lift the produced water, as it is reinjected into the wells directly.

Table A.4 (supplementary material) provides a more detailed list of energy efficient and GHG reducing strategies by target process or system (Oliveira; Van Hombeeck, 1997; Brandt, 2011; El-Houjeiri; Brandt; Duffy, 2013; Pierobon *et al.*, 2014; Voldsund *et al.*, 2014; Nguyen *et al.*, 2014; Nguyen, et al, 2016; Gallo *et al.*, 2017; Rocher; Garnaud, 2017; Riboldi; Nord, 2017; Masnadi *et al.*, 2018a; MAsnadi, *et al.*, 2018b; Farajzadeh, 2019; Farajzadeh, *et al.*, 2021; Farajzadeh, *et al.*, 2022). Most authors suggest strategies involving equipment changes, retrofitting, or significant plant alterations. However, some suggest that emissions could be reduced merely by optimizing the operating strategy (Farajzadeh *et al.*, 2022; Masnadi *et al.*, 2018b; Riboldi; Nord, 2017). The strategies proposed are case-specific, and so they cannot be generalized or replicated for platforms with different operational contexts or fields with varying properties. Therefore, in-depth techno-economic analyses should be performed for each plant (Nguyen, et al, 2016).

Moreover, in the context of LE, not all strategies presented may be applicable. The mindset required to implement strategies for minimizing emissions of a new unit is starkly different from those for minimizing emissions in process upgrades or reconfigurations. The strategy implementation time must be compatible with the extended useful life. Furthermore, the associated implementation costs would also have to be offset by the lower production volume of a mature asset.

5.4 Case Study

The case study was developed for a hypothetical unit (platform A), based on data from the operation of typical platforms in Brazil, and assumptions for the case of LE. Furthermore, the methodology, for analyzing the platform and its GHG emissions, was based on studies of Sánchez and Oliveira (2015), Sánchez (2017) and Barbosa *et al.* (2018). To develop the case study related to the offshore production facility, platform A, the following simplifications and assumptions were adopted: (1) plant is operating since 2008; (2) the design life of the plant is 17 years, that will be reached in 2024; (3) application to the regulator for lifetime extension has to be made 5 years prior to the achievement of design life (2019), as defined by the authors Ferreira *et al.* (2020); (4) there is only one producing well (W1) connected to the unit; (5) Each group of compressors is sized considering the gas flow rate for the year in which the highest production occurs; (6) the necessary heat demand is a function of the oil flow rate. Heat for the process is provided by pressurized hot water. This water is heated using exhaust gases of the gas turbines, and by burning natural gas when needed. Lastly, (7) flare and gas lift systems were not considered in this study.

The case study is presented in the following sections, organized according to the stages of the proposed framework in Figure 5.1, described in Table 5.1.

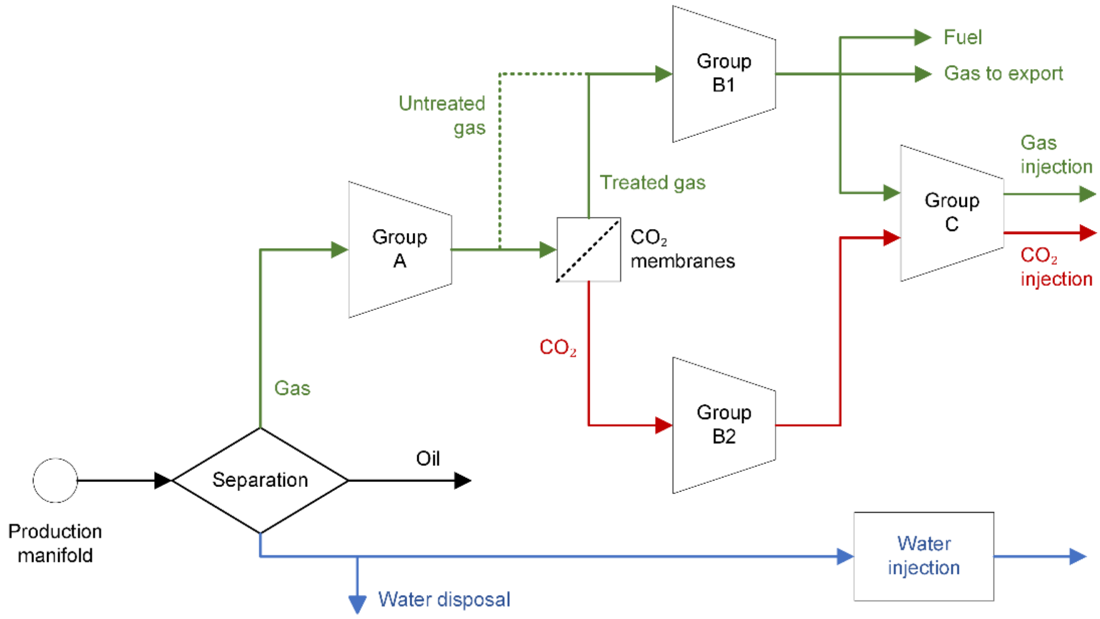
5.4.1 Objective definition (stage 1)

This analysis aims to carry out a diagnosis of the offshore production platform A, to identify opportunities for carbon emission reduction. Identified improvements will make up the LE management plan, the implementation of which will support the facility's LE for another 5 years (until 2029).

5.4.2 Scope definition (stage 2)

The processes and systems, object of the carbon footprint evaluation include the production manifolds, the separation trains, the oil treatment process, the produced water treatment process, the vapour recovery unit (VRU), the gas compression and treatment process, the carbon dioxide compression process, the fuel gas system, the gas turbines and the waste heat recovery process. Figure 5.2 shows the gas compression plant and its interaction with the separation process in the processing plant. Petroleum arrives through the production manifold and is then directed to the treatment and separation train, comprised of a series of separators. In these, gas, oil and water are separated by sequential temperature increases and pressure decreases. The separated oil is directed to storage tanks and produced water is re-injected or discharged into the sea after undergoing treatment (hydrocyclones and decantation) to eliminate the remaining oil (Barbosa *et al.*, 2018).

Figure 5.2 - General overview of an offshore oil and gas platform A processing plant



Legend: in greed – gas flow; in blue – water flow; in red – CO_2 flow; in black – oil flow

Source: Based on Barbosa *et al.*, 2018

The gas is directed to the compression trains, organized in 4 groups (A, B1, B2 and C). In the current operation mode, all gas is first directed to train A. Then, 50% of the gas exiting in train A is directed to CO_2 membranes, while the other 50% goes directly to the B1 compression train. The untreated gas that went directly to B1 goes through the last compression stage, C, and is reinjected into the well. The treated gas from the membranes, with low CO_2 content, also goes through B1 and is then exported. The CO_2 stream in turn, goes through trains B2 and C2, and is injected into the well.

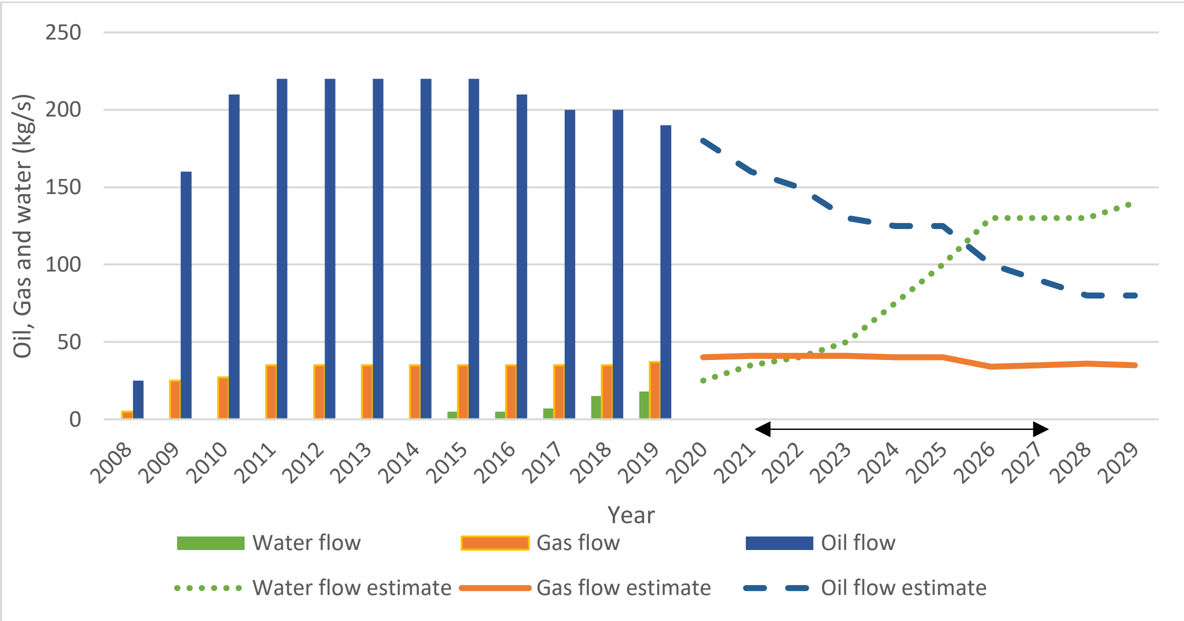
The fuel resulting from group B1 is directed to the utility plant, where it goes through three parallel gas turbines to generate electricity. The utility plant is not illustrated in Figure 5.1, as it is separated from the processing plant. The electricity generated at the utility plant is then directed back to the process plant to power the processes, e.g. pumps, compressors, etc. Exhaust gas from turbines also leaves the utility plant and is used for heating the process plant through waste heat recovery. Throughout the operation, the utility plant uses three turbines to generate power.

The evaluation is carried out when the installation completes 12 years of operational life (2019) and the operator intents to operate for another five years from the end of its designed useful life (2024), that is, until 2029. The analysis is based only on emissions within the control volume presented in Figure 5.2, not including, therefore, those associated with the production of the inputs used by the plant nor those associated with the decommissioning and deactivation phase of the facility.

5.4.3 Field condition description (stage 3)

Field conditions were collected from the only well in production (W1). Field information is summarized in Table A.5 in the supplementary material and the production curve is given in Figure 5.3.

Figure 5.3 - Oil, gas and water production from 2008 (year 1) to 2029 (year 22)



Source: Based on Barbosa *et al.*, 2018

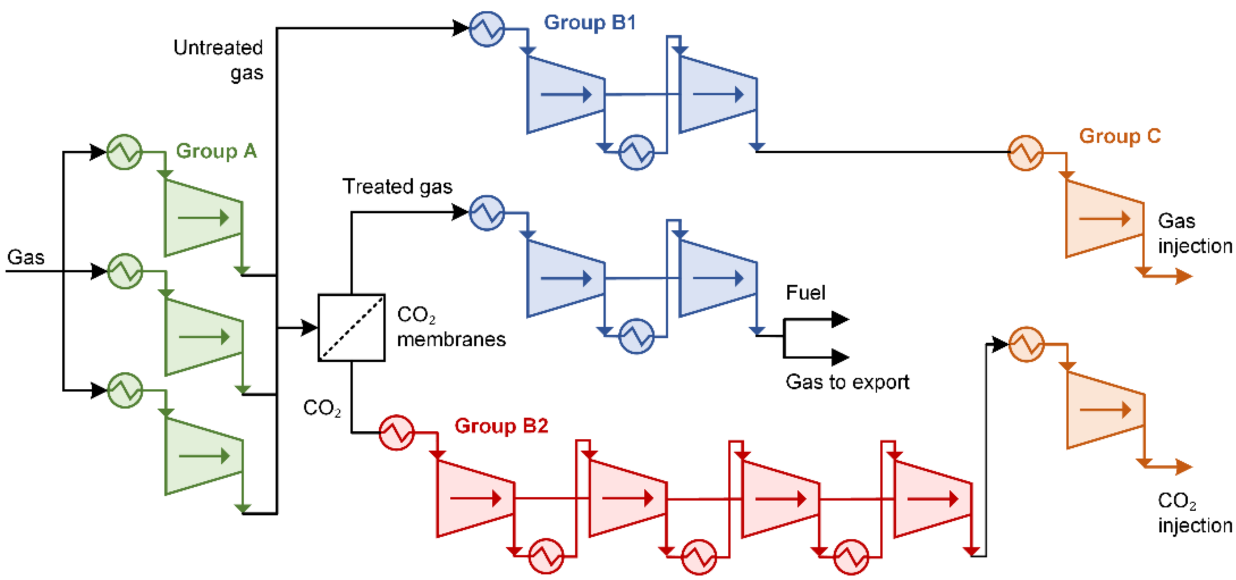
The results of the next stages of the framework (4, 5 and 6) were aggregated and presented in subsection 5.4.4, since the details of each process and subsystem evaluated will not be presented in this case study. For brevity, only one of the evaluated systems, i.e. compression, will be exemplified.

5.4.4 Scope breakdown into manageable portions (stage 4), detailed data collection (stage 5) and input and output definition for each process and system (stage 6)

The general systems and their components in Figure 5.2 were further broken down into smaller processes and subsystems, according to stage 4 of the framework. This additional detailing of the systems facilitates the collection of information in stages 5 and 6. As an example of the breakdown stage, the details related to the compression system are presented in Table A.6 in the supplementary material, according to the description of the system presented by the authors Barbosa *et al.* (2018) (stages 5 and 6 of the framework).

The compression system, organized in 4 groups (A, B1, B2 and C), is further detailed in Figure 5.4. Group A is comprised of three parallel compressors, each with a single compression stage. Group A compresses all produced gas leaving the separation train. Group B1 consists of two parallel compressors with two stages of compression and inter-cooling between stages. Group B is designed to compress all gas produced from group A and the natural gas free of CO_2, which is obtained from the CO_2 membranes. Group B2 comprises one compressor with four stages of compression and inter-cooling between stages. This group is designed to compress solely the CO_2 produced by the CO_2 membranes. Lastly, Group C comprises two single stage compressors, which are designed to compress both produced gas and CO_2.

Figure 5.4 - Detailing of the Compression System



Legend: in green – Group A compressors; in blue – Group B1 compressors; in red – Group B2 compressors; in orange – Group C compressors
Source: The author, 2024

5.4.5 Process modelling (stage 7)

By completing stages 5 and 6 for each process and subsystem, all the required information were obtained to model and simulate the platform. Instead of selecting a ready-made tool, a Python based solver tool was developed by the authors based on the models proposed by Barbosa *et al.* (2018) to model the main equipment of the utility and process plants (separators, pumps, gas turbines, and compressors). This approach was selected based on the scope of the case study and for its cost efficiency and customizability.

5.4.6 Methodology definition for energy demand and inefficiency estimate (stage 8) and monitoring indicator definition (stage 9)

In the same simulation tool developed for stage 7, energy and exergy balance equations were added for the equipment within the scope of the analysis. The focus on exergy was selected according to the recommendation of Nguyen *et al.* (2014), who found exergy analyses, provide a more consistent measure of resource usage, which is better suited for evaluating process performances. Thus, for the case study, the energy (electrical and thermal) and exergy demand were calculated for the main equipment of the utility and process plants. Furthermore, the following indicators were selected according to Sánchez and Oliveira (2015), Sánchez (2017) and Barbosa *et al.* (2018): production indicators (oil and gas production), power requirements indicators (thermal and electrical), energy indicators (gas turbine efficiency, average fuel consumption and energy efficiency), exergy indicator (exergy efficiency) and emissions indicator (CO_2 emissions). The definition of each indicator (unit and identity) and its equations are presented in Table A.7 in the supplementary material.

5.4.7 Performance evaluation (stage 10)

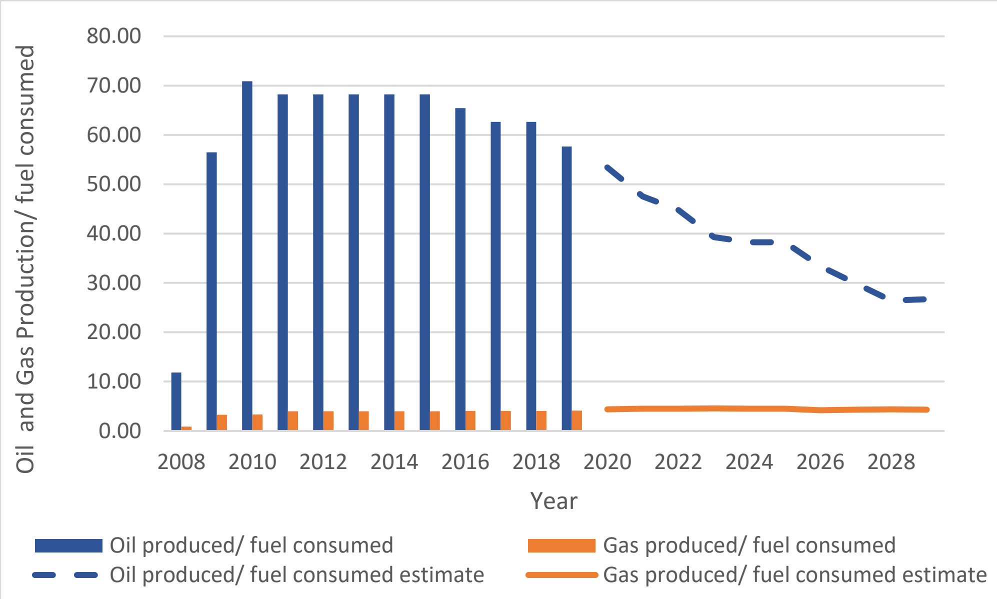
Results of the energy and exergy analyses are shown in Figure 5.5 to Figure 5.11, and Table A.8 (supplementary material) brings the results of the analysis in 2019 (moment of application to the regulator). Based on these results, the following observations and conclusions are presented:

- As expected, at the end of the unit's expected service life, due to depletion, oil production falls and gas production is nearly constant (Figure 5.5), considering that the fuel consumed is relatively constant (Figure 5.8) and that the gas turbine are responsible for the energy generation of the plant.
- At the end of expected service life, considering that new equipment will not be included in the plant, the separation and treatment processes will continue to be responsible for the thermal demand of the plant, as shown in Table A.8 (supplementary material) for 2019.
- From each system analyzed and based on the estimated production of oil and gas, the thermal and electrical demand for the unit is obtained (Figure 5.6).
    - Thermal demand will decrease, mainly because of the reduction in the expected production of oil, which will reduce the demand of the separation process.
    - The largest electrical demands stem from the compressor groups, especially Group A, where the main compression occurs before the CO_2 membrane, and Group B1, with the compression of treated and untreated natural gas (Table A.8 in supplementary material).
    - The electrical demand will have small variation at the end of expected service life, since it depends mainly on the demand coming from the gas compression systems, which, in turn, have little variation over the years (Figure 5.6).
- The efficiency of gas turbines will remain practically constant because of the small variation in electrical demand during the intended extension. These machines operate with little variation in load. The efficiency of gas turbines is around 29% (Figure 5.7). This is based on the use of three turbines throughout operation, which leads to a load of around 85% for each.
- Energy efficiency will decrease over the years mainly due to a reduction in thermal demand, brought upon by the decrease in oil production (Figure 5.9); this occurs because of less energy will be recovered from the exhausted gas of the gas turbine. This reduction in thermal demand does not cause a proportional decrease in the consumption of fuel by

the plant, which remains almost unaffected by the small variation in the plant's electrical demand.

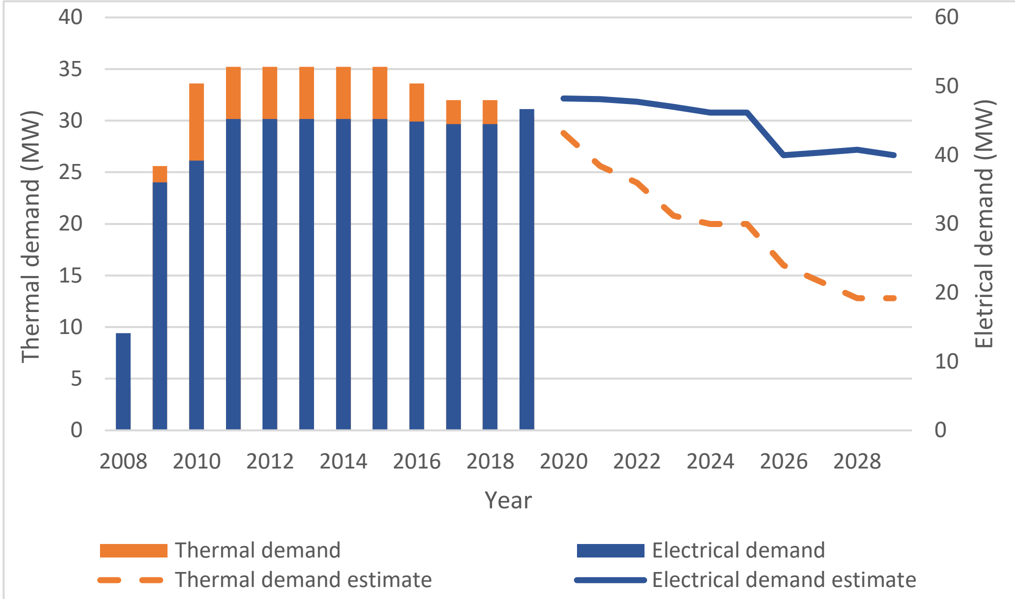
- Exergy efficiency has a less pronounced reduction over the extended life cycle since the thermal demand is more significant for the energy efficiency than for exergy efficiency. So, the reduction in thermal demand will have a greater impact on the former (see Figure 5.10).
- Decreasing plant energy efficiency over the years will result in an increase in emissions of the platform (see Figure 5.11).

Figure 5.5 - Production indicators



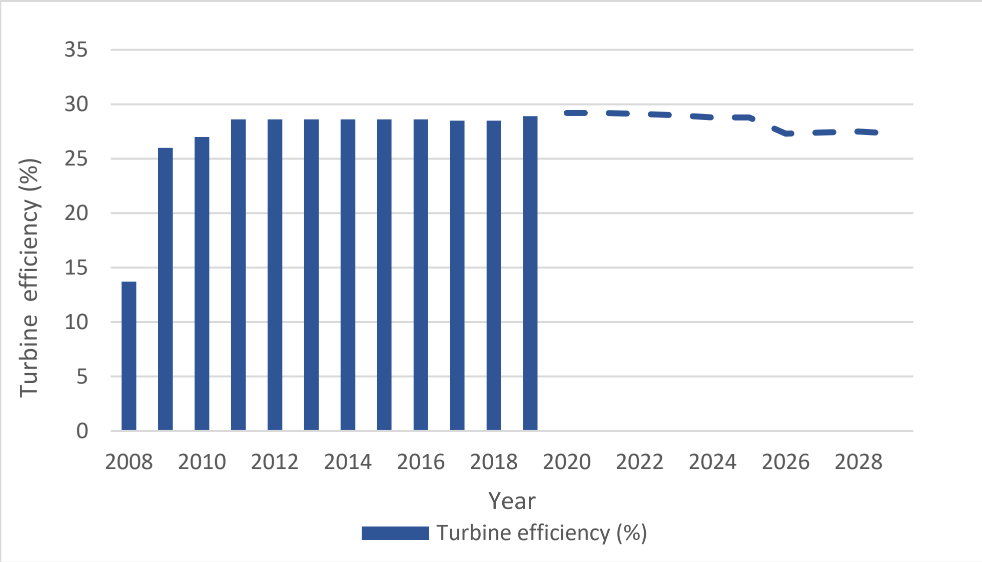
Source: The author, 2024

Figure 5.6 - Power requirements indicators



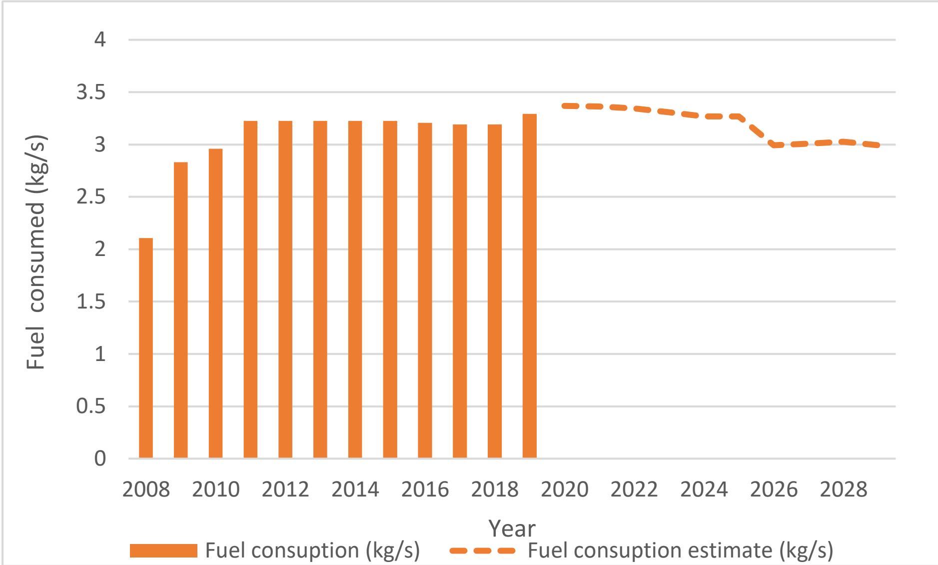
Source: The author, 2024

Figure 5.7 - Energy indicator – gas turbine efficiency



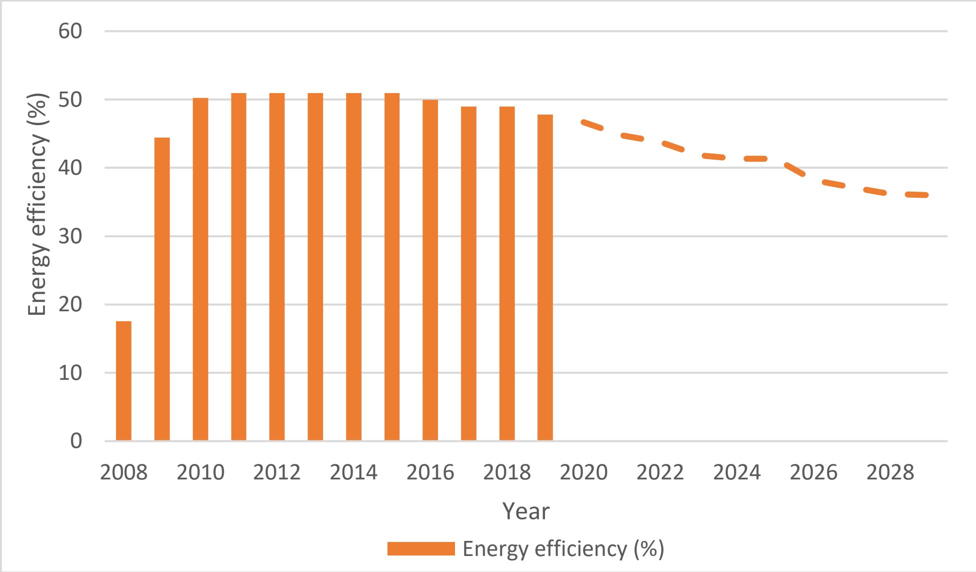
Source: The author, 2024

Figure 5.8 - Energy indicator – fuel consumed in gas turbine



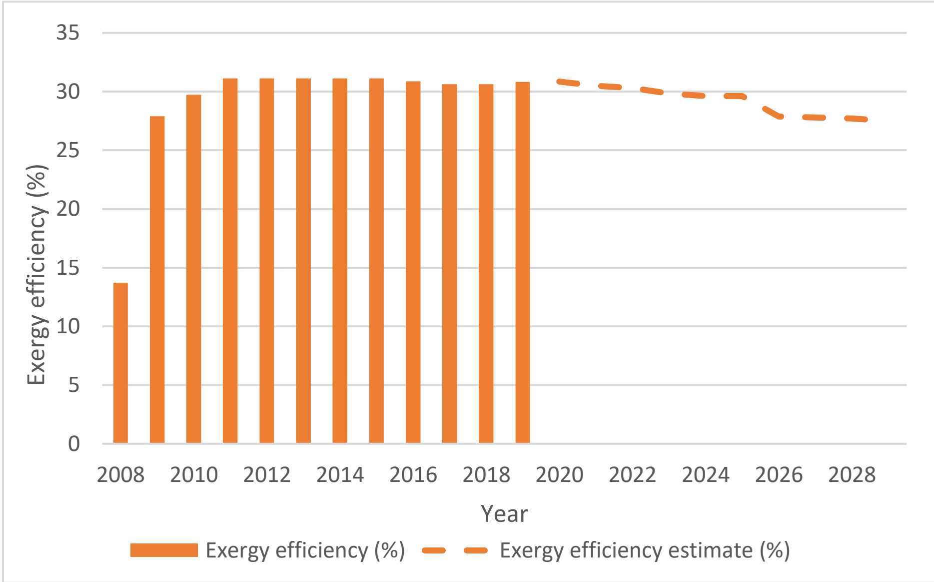
Source: The author, 2024

Figure 5.9 - Energy indicator – energy efficiency



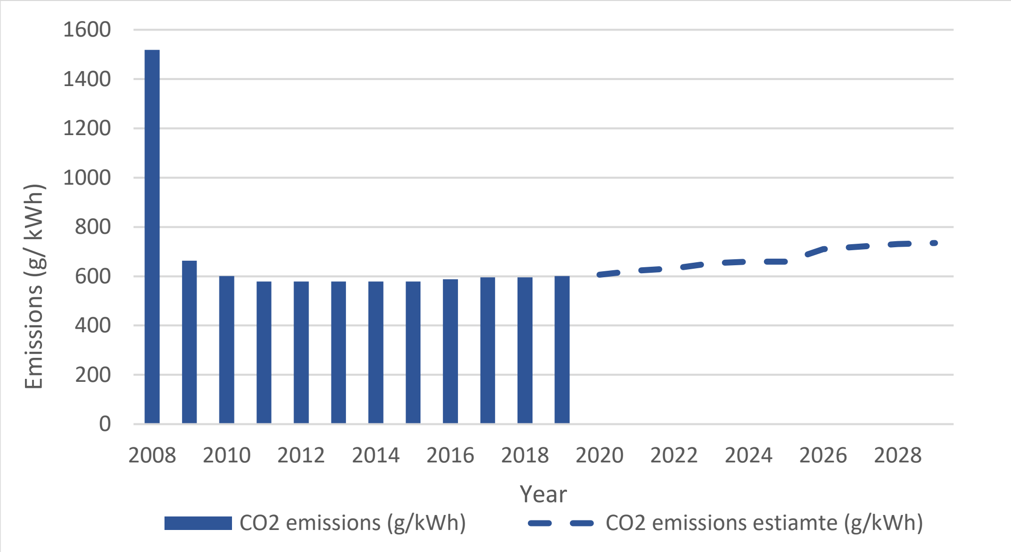
Source: The author, 2024

Figure 5.10 - Exergy indicator



Source: The author, 2024

Figure 5.11 - Emission indicator



Source: The author, 2024

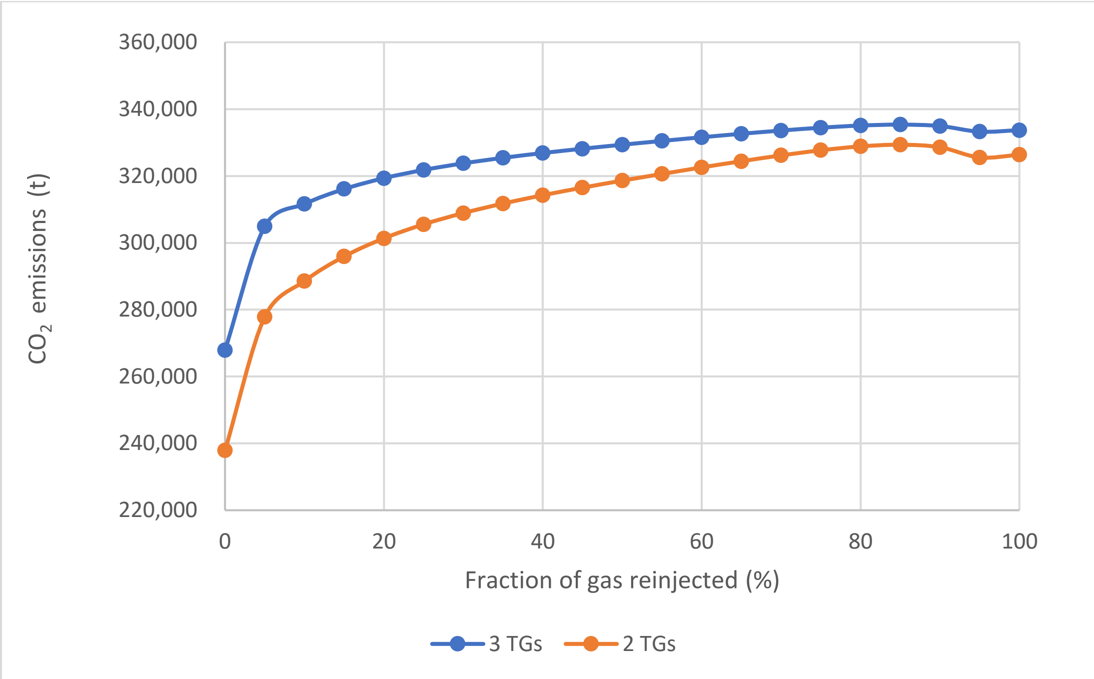
Subsequently, a sensitivity analysis was conducted by evaluating potential changes to the modus operandi of the platform, assuming no new equipment would be installed, and the designed configuration of the compressors would be maintained. This assessment involved variations in two key decision variables:

(i) quantity of turbines in operation – The current configuration with three turbines was considered the baseline scenario. One alternative scenario was defined as operating only two turbines. Operating with a single turbine was not considered viable, as it would fail to meet the energy demands of the platform during its LE period; and

(ii) fraction of gas reinjected and exported from the platform – The baseline was set as the current balanced operation mode (50% gas reinjected and 50% gas exported from the platform). Alternative scenarios were defined by increasing and decreasing these percentages in discrete 5% intervals.

Figure 5.12 shows the impact of variations in these decision variables on CO_2 emissions for the year 2019, marking the first year of the LE. The results revealed that a reduction of one turbine, approximately a 33% decrease in maximum capacity, resulted in a 3.3% decrease in CO_2 emissions (10,745 t), all other parameters being constant. If the same 33% change were applied to the fraction of gas reinjected, the percentage of gas reinjected would be 33.5% and exported 66.5%. All other parameters being constant, this change would lead to by 1.2% reduction in CO_2 emissions (4,101t).

Figure 5.12 - Sensitivity analysis results of varying key decision variables (number of turbines and fraction of gas reinjected) for year 2019



Source: The author, 2024

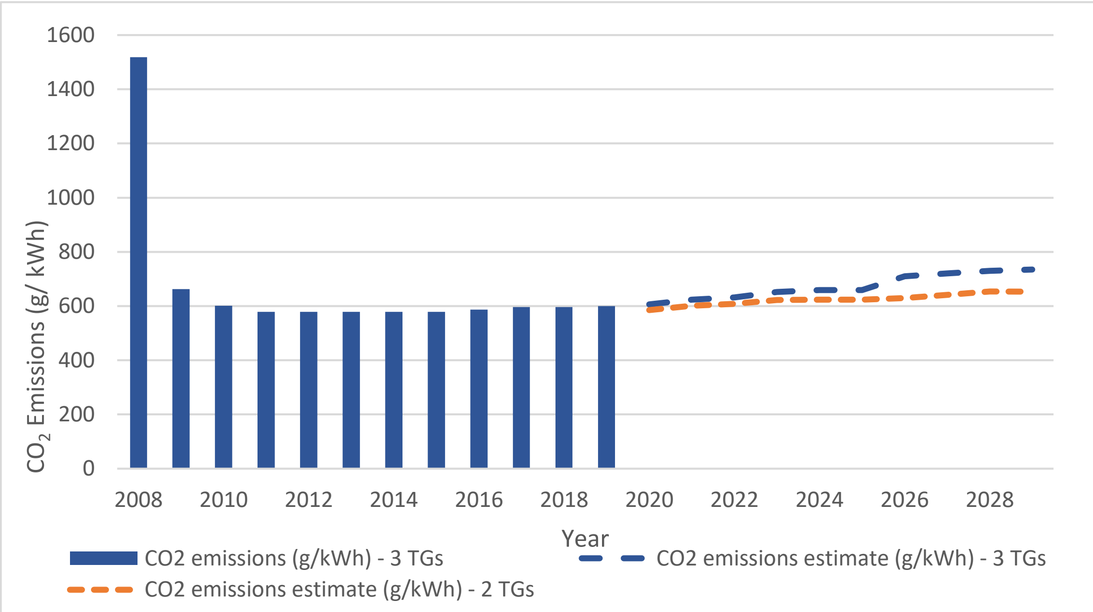
The sensitivity analysis thus demonstrated that variations in both the quantity of turbines in operation and the fraction of gas reinjected and exported significantly influence the overall performance indicators. Drawing from the combined effects of these decision variables, the optimal operational strategy was identified based on achieving the lowest possible CO_2 emissions. The selected strategy will be further detailed in the following subsection.

5.4.8 Interpretation of results (stage 11)

Based on the findings of the performance evaluation, and with the aim of reducing CO_2 emissions during the extension of the useful life of the platform, two key proposals are made. Firstly, based on the results of gas turbine efficiency (Figure 5.7) and the 85% load observed for each turbine, there is an opportunity to increase turbine load, thereby improving efficiency. This could have been implemented even under the current operating mode. Thus, the first proposal is to reduce the number of gas turbines (TGs) in operation from three to two, and increase the load of each turbine, from around 85% to within 90 to 99% during the

LE period. This adjustment allows the turbines to operate closer to their optimum operation point, increasing the efficiency of the generation system. As shown in Figure 5.13, this change in the unit's modus operandi will enable a reduction of 169,400 t CO_2, which represents a 5.3% reduction in GHG emissions in the next 10 years of operation. This change will also imply a reduction of 53,420 t in expected fuel consumption in the same period.

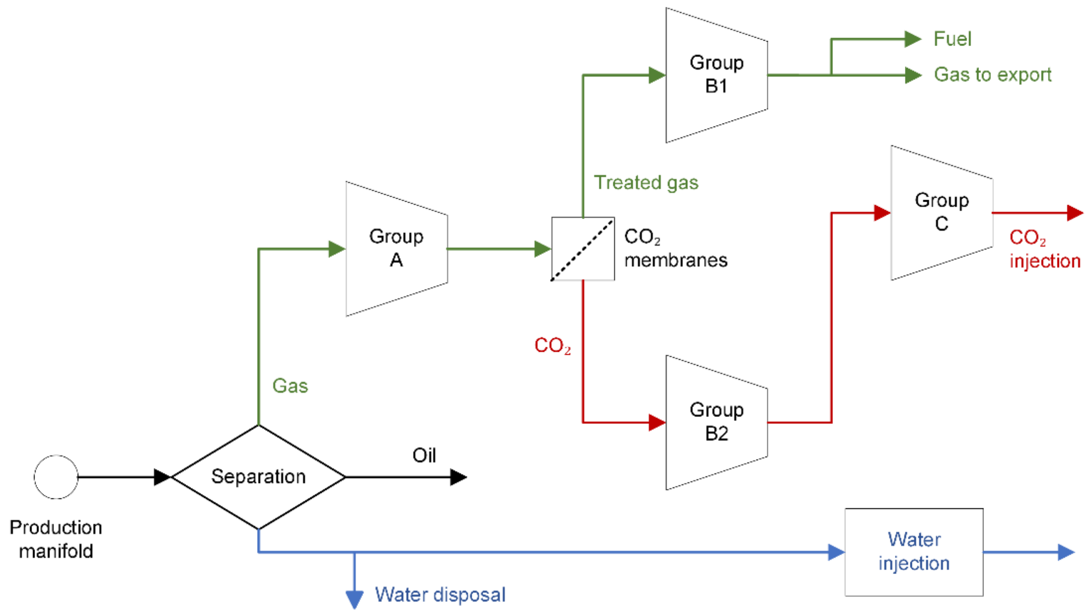
Figure 5.13 - Comparison between operations with two or three turbines in terms CO_2 emission



Source: The author, 2024

Secondly, because electrical demand has small variation during the LE and the largest electrical demands stem from the compressor groups (Table A.8 in supplementary material), these were also identified as an area for improvement. The second proposal consists of changing the current unit operating condition, described in section 5.4.2, so that all treated natural gas is exported (except from the part used as a fuel), and CO_2 is injected, as presented in Figure 5.14.

Figure 5.14 - Operational mode – exportation exclusive



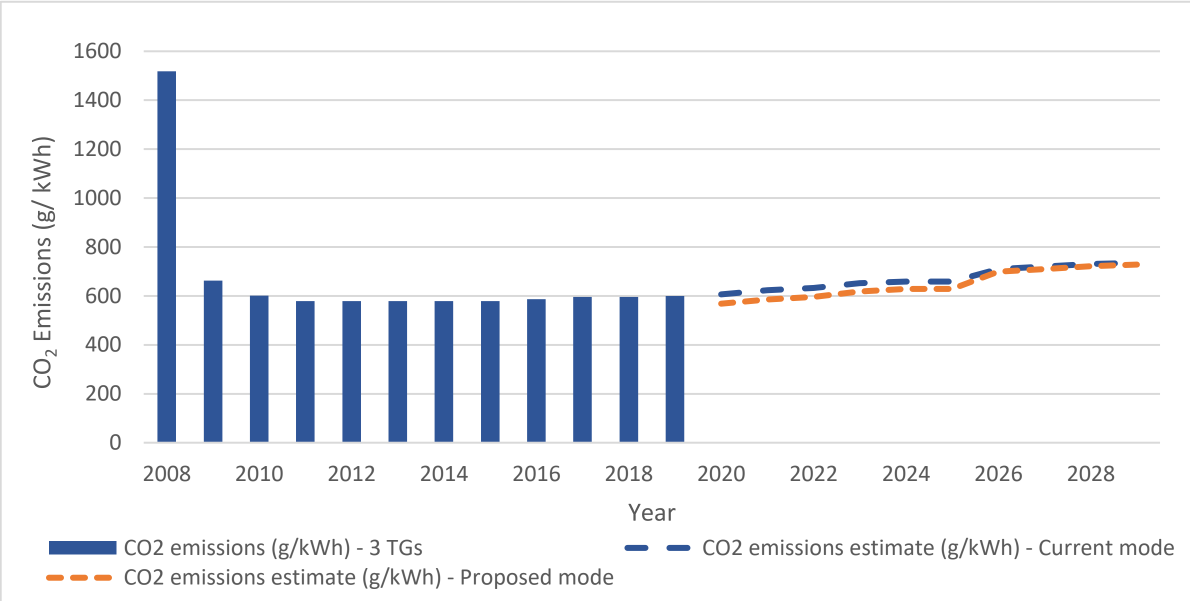
Legend: in greed – gas flow; in blue – water flow; in red – CO_2 flow; in black – oil flow

Source: The author, 2024

Based on this second proposal, a reduction of 590,800t CO_2 emissions is expected, which represents a 18.5% reduction in the next 10 years of operation, compared to the base scenario of three turbines. This significant reduction is due to the demand for electricity by the compressors. Because the untreated gas no longer passes through compression train B1 and the gases from group B1 no longer pass through compression train C (Figure 5.14) the electricity demand in B1 and C compression trains is, respectively, 25% and 20% lower.

Figure 5.15 shows that the CO_2 emission indices remain similar, being difficult to visualize the absolute reduction in CO_2 emission in later years. This is because the proposed operation mode has a significant reduction in emissions but is accompanied by a reduction in electricity demand (index denominator), leading to little change in the normalized index.

Figure 5.15 - Comparison between current and proposed modes of operation in terms of CO_2 emission



Source: The author, 2024

Combining the two proposals described above, a reduction of 922,000 tCO_2 is expected, which represents a 28.9% reduction in the next 10 years of operation. The first proposal increased the energy efficiency of the gas turbines, specifically, and the second improved the energy performance of the platform by avoiding the injection of natural gas into the wells and exporting it completely instead. Both strategies could be implemented by altering the unit's operation, without altering the plant layout or requiring capital investment.

As a limitation, it should also be noted that two key assumptions were made in the case study analysis. In the first proposal, the use of two turbines instead of three was assumed to not impact the reliability of the system, considering that the third would be on standby. In the second proposal, the injection of CO_2 was assumed to be sufficient for EOR. In other cases, these assumptions would have to be validated, and other aspects besides energy efficiency and emissions should be considered. In parallel with the assessment of GHG emissions, the broader LE decision-making framework proposed by Ferreira *et al.* (2020) would consider material degradation, obsolescence, and organizational issues. Further analysis of strategy costs and regulatory approval would also be completed once all these technical evaluations are completed, feeding into of the economic decision on whether to extend the asset and the development of the LE management plan.

5.5 Conclusion

The pressing need to globally reduce GHG emissions and the increasing number of oil field units being operated beyond their expected useful life, at higher emission rates, should prompt the oil and gas industry to include emissions assessments in LE decision-making process. To this end, this study proposes the inclusion of a GHG emission assessment in LE decision-making, a neglected factor in literature and international regulation. This assessment adds to the existing evaluation criteria of material degradation, obsolescence, and organizational issues, completing the technical evaluation of LE, as designated by Ferreira et. al (2020). Thus, to incorporate such assessment, an eleven-stage framework was developed, with the following stages: (1) Objective definition, (2) Scope definition, (3) Field conditions description, (4) Scope breakdown into manageable portions, (5) Detailed data collection for each process and subsystem, (6) Input and output definition for each process and subsystem, (7) Process modeling, (8) Methodology definition for energy demand and inefficiency estimate, (9) Monitoring indicator definition, (10) Performance evaluation, and (11) Interpretation of results.

A case study was conducted to validate the application of the proposed framework. The case study is based on data from typical platforms operating in Brazil, with a focus on the equipment of the utility and process plant (separators, pumps, gas turbines, and compressors). Using the proposed framework, a potential LE scenario was analysed, and two improvement strategies were considered, i.e. reducing the number of gas turbines and increasing the export of natural gas. These solutions address the unit's modus operandi, without altering the plant layout or requiring capital investment. Compared to the original operations, the proposed strategies were found to reduce GHG emissions by 922,000 CO_2, which represents a 28.9% reduction in the next 10 years of operation. Further disruptive measures might offer larger energy efficiency gains and deserve more in-depth exploration. Table A.3 in the supplementary material presents a comprehensive literature review of various additional methodologies, scopes, and strategies for mitigating carbon emissions, providing valuable insights for operators.

The proposed framework's application to the case study highlights its value in three ways, as follows: (i) its ability to systemically assess GHG emissions in LE contexts, offering a simplified and effective decision-making basis, (ii) its capacity to enable the identification of solutions that lead to significant improvements in energy efficiency and (iii) its potential to assist operators and regulatory agencies in preparing and evaluating LE management plan, despite the lack of regulatory requirements for carbon footprint assessments, as is the case in Brazil. It should be noted that the case study validated the framework itself, but the selection of indicators and methodologies for simulating and optimizing the systems will depend on the granularity of the available data/information, the complexity of the system under evaluation, and the tools at hand. Furthermore, the application of the proposed framework to a simple case illustrates the potential benefits of its application in a real-world setting with multiple processes. The application to a real unit, due to the extensive number of parameters involved, would necessitate the use of optimization tools, and could lead to further significant improvements in energy efficiency and the reduction of inefficiencies.

Following the application of the proposed framework, next steps in the LE management process, as defined by Ferreira *et al.* (2020), would be the assessment of economic issues and the evaluation of regulatory compliance. These were outside the scope of the present study, since they must consider all the aspects of the LE, i.e. material degradation, obsolescence, organizational issues and carbon footprint, not only this last aspect in isolation. Combined, these parameters would yield a holistic assessment of oil and gas field LE.

CONCLUSIONS AND SUGGESTIONS

Conclusions

As oil and gas facilities age, extending their operational life becomes increasingly crucial to operators to maintain their asset producing while ensuring safety and environmental compliance. Life extension (LE) of these ageing assets involves complex decision-making processes that require a comprehensive evaluation. This research provides a thorough examination of the key factors involved in the LE of offshore oil and gas facilities, integrating technical, organizational, and environmental aspects into a unified decision-making framework, a structured **Life Extension Methodology** to manage the life extension of offshore assets.

The proposed framework is comprised of twelve stages detailed and subcategorized in a set of activities: (i) definition of LE motivation; (ii) definition of LE period; (iii) definition of LE premises; (iv) evaluation of asset condition; (v) assessment of RUL; (vi) evaluation of obsolescence and organizational issues; (vi) definition of LE strategy; (vii) definition of LE strategy; (viii) assessment of economic issues; (ix) definition of a LE Management Plan; (x) obtaining regulatory approval; (xi) implementation of LE Management Plan and (xii) monitoring the LE Management Plan effectiveness. The application of this framework in both real and hypothetical case studies, which focused especially on the first key-aspect of life extension (**Material Degradation**), demonstrated its effectiveness in transforming the LE decision-making process into a systematic and transparent procedure, ultimately enhancing asset management during extended operation periods.

In terms of **Obsolescence Management**, the research focused on addressing the four key drivers of obsolescence - availability or support from manufacturers, new requirements or demands, new technologies, and new conditions or needs - in LE decision-making. Furthermore, a six-stage methodology was introduced to manage the obsolescence in the context of LE: (i) breaking down the systems into manageable portions; (ii) development of a database; (iii) assessment of obsolescence; (iv) identification of the condition of SSCs; identification of SSCs that are also barriers to operational safety; and categorization of SSCs according to the obsolescence temporal status; (v) definition of priorities; and (vi) reevaluating continuously. The importance of integrating obsolescence assessment into the broader LE framework was emphasized, and the proposed methodology was validated through a hypothetical case study, demonstrating its applicability across various asset types and industries.

In terms of **Organizational issues,** among the aspects that can influence the success of extending the operational life of oil and gas facilities**,** the research focused on the challenges of interorganizational knowledge transfer (IKT), considering the context of increasing acquisition of older oil and gas facilities by companies that intent to extend their lives. Based on the examination of a case study of an ageing platform, transferred between two companies and future LE by the buyer company, 22 key elements and 27 challenges were identified that need to be managed for an effective knowledge transfer. This research filled existing gaps on organizational issues related to LE, highlighting the need for a more detailed understanding of IKT in the context of facility acquisitions.

The study further explored IKT challenges, focusing on their impact on process safety. It distinguished IKT elements by their criticality to process safety and identified specific challenges unique to onshore and offshore environments. A direct connection was established between IKT failures and compromised elements of Risk-Based Process Safety (RBPS), particularly in Process Knowledge Management. The findings underscored the necessity of including IKT considerations in the LE decision-making process to maintain operational safety.

The research also addressed the need to incorporate **Greenhouse Gas (GHG) Emission Assessment** into the LE decision-making process. An eleven-stage framework was proposed for systematically evaluating emissions, with the following stages: (i) Objective definition, (ii) Scope definition, (iii) Field conditions description, (iv) Scope breakdown into manageable portions, (v) Detailed data collection for each process and subsystem, (vi) Input and output definition for each process and subsystem, (vii) Process modeling, (viii) Methodology definition for energy demand and inefficiency estimate, (ix) Monitoring indicator definition, (x) Performance evaluation, and (xi) Interpretation of results. The application of this framework through a case study of typical Brazilian offshore platforms demonstrated its potential to significantly reduce emissions and improve energy efficiency, adding a new dimension to LE assessments that extends beyond material degradation, obsolescence and organizational issues.

The importance of integrating all the mentioned technical, organizational and environmental considerations into LE strategies, assessment of economic issues, and definition of the LE Management Plan to guarantee appropriate management of LE is highlighted in the research.

Regarding the definition of strategies that will form the LE Management Plan, it is important to note that, although numerous options for mitigating the risks associated with the ageing process have been drawn from the literature throughout the chapters, not all of them are applicable to the timing specific to life extension (LE). This phase is characterized by a mature field and other limitations imposed by the asset. The strategies presented in the literature are often comprehensive when addressing, for instance, emission reduction for new units, but remain silent concerning units operating beyond their design life. Therefore, it is crucial to seek strategies that are specifically aligned with the current stage of the asset. In this context, evaluating the economic aspects associated with the implementation of these strategies becomes a key factor. While Stage 8 of the proposed framework in Chapter 1 was developed in a simplified manner and not further explored in subsequent chapters—given that it is not the primary focus of this work—it remains a critical issue for determining the "go/no-go" decision in the life extension process.

Overall, this research contributed to a more comprehensive approach to managing the life extension of offshore oil and gas facilities. The integration of technical, organizational, and environmental factors into a cohesive LE framework offers operators and regulators a robust tool for making informed decisions, ultimately enhancing the safety and reduced emissions of extended operations.

Suggestions

To complement this research, the following suggestion are made for future work:

1. **Application of Life Extension Methodology proposed to diverse assets.** Future studies should explore the application of the proposed life extension (LE) methodology across different types of assets and industries to help refine the framework and ensure its adaptability to a broader range of scenarios. In this regard, particular attention should be given to understanding and supporting Step 10 of the framework developed in Chapter 1, considering the specific characteristics of each industry. This includes analyzing the role of the regulator - whether more or less participative in the process of developing and/or approving the LE Plan -

and determining whether they impose mandatory requirements or provide guidelines for the life extension period.

2. **Exploration of IKT elements and challenges from multiple perspectives.** Given the limitations of the current study, which focused on the perspective of one company, future research should investigate the differences in IKT challenges from the perspectives of both the source and recipient organizations to provide a more comprehensive understanding of the dynamics involved.

3. **Incorporation of Organizational Issues into the LE decision-making process.** More research is needed to evaluate how organizational issues, such as inter-organizational knowledge transfer (IKT), impact the LE process, particularly how they affect operational performance and safety. Studies could explore how these issues influence decision-making and operational outcomes in various industries and contexts and propose the development of a frameworks for managing knowledge transfer during asset acquisition and life extension.

4. **Development of a More Comprehensive GHG Emission Assessment.** Given the potential benefits demonstrated in the case study, further research should explore the development of advanced optimization tools to maximize energy efficiency and minimize emissions in real-world settings and expand the scope of analysis to include the venting, flaring and fugitive (VFF) emissions. This could lead to significant improvements in the environmental performance of ageing oil and gas facilities.

5. **Interconnections Between Material Degradation, Obsolescence, Organizational issues and GHG Emissions**: There is an opportunity for future research to investigate the interconnections between material degradation, obsolescence, and GHG emissions in the context of life extension. Understanding these relationships could lead to a more holistic approach to LE assessments.

6. **Analysis of Successful and Unsuccessful Life Extension Programs in Various Industries**: Future research should explore life extension programs that have succeeded or failed in the oil and gas industry, as well as in other industries. This presents a valuable opportunity to compare these programs with the proposed life extension frameworks, identifying gaps and strengths in their implementation. Such comparisons will help researchers and practitioners understand the completeness or shortcomings of these programs, offering critical insights for improving future LE projects.

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APPENDIX A – Supplementary Material of Article 3

Table A.1 – Interview Protocol (initial questions)

Preliminary questions
1. Position/role in the company before the process of buying/selling the facility.
2. Position/role during interorganizational knowledge transfer
General questions
1. How did knowledge transfer take place between the two companies?
2. What knowledge would you list as the object of knowledge transfer? What are the main characteristics of this knowledge?
3. What were the biggest challenges? Could you name any specific barriers to knowledge transfer?
4. What aspects facilitated knowledge transfer?

Source: The author, 2024

Table A.2 – Interview Protocol (main questions)

Second-order Construct	Environment (*)		Informant Profile (**)			Questions
	ON	OFF	TM	MM	EM	
Structural Governance	X	X	X	X		How was the decision-making process? (follow-up questions, if necessary): - Was it unilateral (one company), consensual, hybrid? - Was it defined on a case-by-case basis, semi structured, or structured (defined for all decisions)?
	X	X	X	X		How was the conflict-resolution process?

Second-order Construct	Environment (*)		Informant Profile (**)			Questions
	ON	OFF	TM	MM	EM	
						(follow-up questions, if necessary): - Was it defined on a case-by-case basis, or previously established?
	X		X			How was the contract established with regards to knowledge transfer? (follow-up questions, if necessary): - Was it standardized or specific for the agreement between the two companies? - Did it address the transfer of knowledge clearly and explicitly? - Was it adequate for promoting the transfer of knowledge? - Did it enable the exchange of information and knowledge in an unrestricted way? Or did it make it difficult?
Related absorptive capacity	X	X	X	X		With regards to corporate procedures... - How would you characterize the two companies?
	X	X		X	X	With regards to operating procedures... - How would you characterize the two companies?
	X	X	X	X	X	With regards to operational safety management system... - How would you characterize the two companies?
	X	X	X	X	X	With regards to organizational structure... - How would you characterize the two companies?
	X	X	X	X	X	With regards to safety culture... - How would you characterize the two companies?
	X	X	X	X	X	With regards to what was learned from the other company... - How would you characterize the two companies?
	X	X	X	X	X	Was there any content that you had difficulty understanding, assimilating or putting into practice later?

Second-order Construct	Environment (*)		Informant Profile (**)			Questions
	ON	OFF	TM	MM	EM	
Motivation	X	X	X	X	X	What was your willingness/ readiness to transfer knowledge? (follow-up questions, if necessary): - In terms of the time available. - In terms of commitment. - In terms of identifying the right people and making it easier to get in touch with those people?
	X	X	X	X	X	What was your counterpart's willingness/ readiness for knowledge transfer? (follow-up questions, if necessary): - In terms of the time available. - In terms of commitment. - In terms of identifying the right people and making it easier to get in touch with those people?
	X	X	X	X	X	How would you characterize the interest in knowledge transfer for both companies? (follow-up questions, if necessary): - Was it a balanced interest between the parties, or totally one-sided?
Prior experience	X	X	X	X	X	To what extent were the previous knowledge transfer experiences of the two companies different or like this transfer? (follow-up questions, if necessary): - What were the points of convergence? - What were the points of divergence?
	X	X	X	X	X	To what extent did the previous knowledge transfer experiences of the two companies help or hinder this transfer? (follow-up questions, if necessary): - What were lessons learned that contributed to the knowledge transfer? - What were lessons learned that did not contribute to the knowledge transfer?

Second-order Construct	Environment (*)		Informant Profile (**)			Questions
	ON	OFF	TM	MM	EM	
	X	X	X	X	X	Which mechanisms were used by the company to codify lessons learned from previous knowledge transfer experiences?
Training	X	X	X	X	X	Were there any issues/topics for which training from the source company was requested? (follow-up questions, if applicable): - Did the source company provide the training as requested? - Was the training effective? Did it help in assimilating the knowledge? - Explain (content, process, technique) that the company had be trained to understand.
Management capacity	X	X	X	X	X	How were the objectives of the knowledge transfer established? (follow-up questions, if necessary): - When were they defined: before the transfer, during the transfer, or never? - Who defined them? - Were they defined explicitly or implicitly? Formally or informally?
	X	X	X	X	X	How was the scope of the knowledge transfer established? (follow-up questions, if necessary): - When was it defined: before the transfer, during the transfer, or never? - Who defined it? - Was it defined explicitly or implicitly? Formally or informally?
	X	X	X	X	X	What was the level of cooperation between the two companies? (follow-up questions, if necessary): - When was it defined: before the transfer, during the transfer, or never? - Who defined it? - Was it defined explicitly or implicitly? Formally or informally??
	X	X	X	X		Was there a team or a person responsible for coordinating knowledge transfer as a whole, including onshore

Second-order Construct	Environment (*)		Informant Profile (**)			Questions
	ON	OFF	TM	MM	EM	
						and offshore? (follow-up questions, if applicable): - How was the interface of this team or person with the different environments within the company (on and offshore)? - What is the organizational level of this team or person?
	X	X	X	X	X	How was the progress of knowledge transfer monitored? (follow-up questions, if necessary): - What was the frequency and content of the feedback? - To whom was the feedback reported?
Inter-organizational routines	X	X	X	X	X	Were routines defined between the counterparts of the two companies? (follow-up questions, if applicable): - How were these routines defined (unilaterally by one of the companies or established consensually)? - Provide examples of some routines created to coordinate and facilitate knowledge transfer and who was involved in the creation of these routines. - Explain what the routine was like between you and your counterpart in terms of knowledge transfer.
Other coordination tools	X	X	X	X	X	How was access to the unit's operation and safety database provided? (follow-up questions, if necessary): - Was it centralized or decentralized? Explain. - Were there any conflicts regarding data transfer? Explain. - Who defined the method for data transfer? Was this method appropriate, or did it hinder knowledge transfer?
	X	X	X	X	X	What were the mechanisms used for knowledge transfer? (follow-up questions, if necessary):

Second-order Construct	Environment (*)		Informant Profile (**)			Questions
	ON	OFF	TM	MM	EM	
						- Who defined the mechanisms? Were they considered appropriate, or did they hinder knowledge transfer?
Time	X	X	X	X	X	How was knowledge transfer spread over time? (follow-up questions, if necessary): - More punctually or continuously during the transition phase?
	X	X	X	X	X	Do you believe that the transfer duration was adequate for knowledge transfer? (follow-up questions, if necessary): - Was there enough time for the assimilation of the unit's operational and safety issues?
	X	X	X	X	X	Do you think that, over time, knowledge transfer improved? (follow-up questions, if applicable): - What would have sped up the process? - What made the process difficult?
Due diligence	X		X			Was any due diligence carried out prior to the start of the transfer? (follow-up questions, if applicable): - What was the scope of due diligence? - What important points were raised in the due diligence regarding knowledge transfer? - Was the information collected for due diligence used later? (follow-up questions, if necessary): - Overall, how did due diligence contribute to the subsequent knowledge transfer process? - Were any gaps identified between the two companies during due diligence?

(*) Informant-based environment: ON – onshore; OFF – offshore; (**) Interviewees hierarchical position: TM - Top Manager; MM - Middle Manager; EM – Employee]
Source: The author, 2024

APPENDIX B – Supplementary Material of Article 5

Table A.3 - Findings of studies related to oil and gas facilities and approaches to reduce carbon footprint.

Authors	Field/ Facilities	System boundary	Scope	Target processes/ system	Properties driving emissions	Strategies for reducing emissions
Masnadi *et al.* (2018a)	146 large oilfields from 20 countries, which supply to the Chinese oil market	Well to refinery (crude oil extraction and transport)	Emissions and energy efficiency	Surface processing EOR with intensive steam and gas flooding Flaring	Low productive reservoirs High WOR	Implement an adequate gas treatment and transportation infrastructure that can avoid excessive flaring.
El-Houjeiri, Brand and Duffy (2013)	4 fictional fields based on real California oil fields, with different operational characteristics	Well to refinery (crude oil extraction and transport)	Emissions	Surface processing Steam injection Flaring Venting	High WOR High GOR Greater field depths (especially with high WOR) Field depletion Heavy oil	Investigate the application of a heater or treater in surface oil−water separation, mainly at high WOR.
Masnadi *et al.* (2018b)	8966 on-stream oil fields in 90 countries, including onshore and offshore; and conventional and unconventional fields	Well to refinery (crude oil extraction and transport)	Emissions and costs	Surface processing Flaring Venting	Heavy oils Energy inputs with high carbon intensity	Install solar-powered steam generators. Prioritize less carbon-intensive assets (e.g., tight oil). Use energy inputs with low carbon intensity (e.g. hydrogen sourced from wind and biomass) Capture CO_2 from oil sands extraction. Make some upgrades in facilities. Manage flaring and venting stringently. Implement an adequate transportation infrastructure to avoid excessive flaring. Continuously monitor and verify flare, vent and fugitive emissions (e.g., modern surveillance using remote-sensing

Authors	Field/ Facilities	System boundary	Scope	Target processes/ system	Properties driving emissions	Strategies for reducing emissions
						technologies. In new oil fields, eliminate routine flaring (e.g., using conservation methods of capture, utilization and/or reinjection).
Brandt (2011)	306 California oilfields	Well to refinery, refining and fuel combustion.	Energy efficiency	Steam injection Steam generation	High WOR Well depth Field depletion	An increase in technical efficiency in drilling, lifting, steam injection and refining was not found to compensate for the reduced quality of oil over (e.g., higher WOR).
Voldsund *et al.* (2014)	4 North Sea platforms type	Well to refinery (crude oil extraction and transport)	Exergy destruction and energy efficiency	Production manifolds Separation Coolling Gas compression Anti-surge recycling Gas injection Flaring	Inefficient equipment and system Field depletion	Design production manifolds at several pressure levels. Integrate multiphase expanders in the production manifold or multiphase ejectors. In the gas treatment, re-wheel compressors and integrate several parallel trains. In the utility plant, replace conventional combustion technologies with combined cycles. Manage flaring.
Rocher and Garnaud (2017)	Oil facilities that deal with mature oil assets with no gas market for valorisation of associated gas	Well to refinery (crude oil extraction and transport)	Energy demand	Gas compression Power generation	Inefficient operational procedures Inefficient equipment	Optimize operating conditions, including improvement of rotating machines operations. Re-route flows sent to vent or flare. Recover flows such as by blanketing gas on some equipment or flash drum vapours. Install better metering initially to improve consumption monitoring. Use energy efficient turbines. Install WHRU on turbine exhaust gas. Use ultra sonic flow meters on flares. Implement energy efficient procedures to restart the installation after shutting down. Install dry gas seals on compressors. Tune plant control loop.
Nguyen *et al.* (2014)	Norwegian oil field in Continental Shelf	Processing and utility plants	Energy efficiency	Reboiling of	Oil depletion	Electrify the oil and gas platform.

Authors	Field/ Facilities	System boundary	Scope	Target processes/ system	Properties driving emissions	Strategies for reducing emissions
	region with facility in 3 exploitation periods			condensate stripping column Heating system Gas Compression Anti-surge recycling Power generation	High WOR	Implement waste heat recovery cycles. Integrate a steam Rankine cycle.
Nguyen *et al.* (2016)	Oil and gas platforms in Norwegian oil field in Continental Shelf region, that is approaching its end-life	Processing and utility plants	Emissions	Power generation CO_2-capture process	High WOR Field depletion	Implement waste heat recovery with a steam network. Installation of a CO_2-capture unit. Electrify of the platform.
Farajzadeh (2019)	Oil fields	Water injection process	Emissions	Water injection	High WOR	Reduce of water cut. Manage water.
Farajzadeh *et al.* (2022)	2 oilfields in the Middle East	IOR and EOR process	Emissions	Water injection Gas EOR Chemical EOR	High WOR	Substitute fossil fuel-based power sources with renewables. Manage water in water drive recovery of oil. Efficiently use injectants through I/EOR methods. Use polymer flooding (for high permeable medium-heavy oil reservoir).
Farajzadeh *et al.* (2021)	2 oilfields in the Middle East	IOR process	Emissions	Water injection Gas EOR Chemical EOR	High WOR	Use polymer injection.
Oliveira Junio and Van Hombeeck (1997)	Oil and gas Brazilian platform	Offshore platform separation system (separation, compression, and pumping)	Exergy destruction and energy and exergy efficiency	Heating system Gas compression Separation	Differences between the separation temperature and the combustion/exhaust gases temperature.	Implement heat recovery from gas turbine exhaust. Monitor the platform to evaluate efforts on adapting to changing process conditions or on increasing the process efficiency. Set correct separation temperature.
Gallo *et al.* (2017)	Oil field with different conditions:	Offshore platform Compression systems	Energy efficiency	Gas compression Anti-surge recycling	High WOR Field depletion	Recover exergy of the cooling water. Reduce hot water in the cogeneration system (TG). Explore a bottoming cycle in the gas turbines.

Authors	Field/ Facilities	System boundary	Scope	Target processes/ system	Properties driving emissions	Strategies for reducing emissions
	maximum oil and gas production and off design condition (50% BSW and WOR)			Power generation		Install smaller compressors in parallel.
Pierobon *et al.* (2014)	Offshore platform in the North Sea	Offshore platform gas turbine-based power system.	Energy efficiency	Heating system	---	Increase the heat transfer area. Implement an organic Rankine cycle. Implement a steam Rankine cycle.
Riboldi and Nord (2017)	2 offshore installations in the North Sea	Offshore platform power system	Emissions	Power generation	---	Implement on-site power generation. Implement full plant electrification. Select the best share between local power generation and power from shore. Optimize the load share between the plant and the gas turbines. Integrate a wind farm into an offshore combined cycle power plant.

WOR – water−oil ratio or water cut or produced water; SOR – steam−oil ratio; GOR – gas−oil ratio; IOR/EOR – improved and enhanced oil recovery; TEOR – thermal enhanced oil recovery; WHRU – Waste Heat Recovery Unit; BSW - Basic sediment and water.

Source: The author, 2024

Table A.4 - Summary of strategies for reducing emissions by target process or system applied in previous studies

Target process/ system	Strategies
Surface processing	Prioritize less carbon-intensive assets (e.g., tight oil)
	Manage water in water drive recovery of oil
Separation	Implement a heater or treater in separation
	Recover exergy destructed
	Set correct separation temperature
Production manifolds	Design production manifolds at several pressure levels
	Exploit exergy in ejectors and expanders
	Integrate multiphase expanders or multiphase ejectors
Injection	Efficiently use injectants through I/EOR methods
	Use polymer flooding (for high permeable medium-heavy oil reservoir)
Gas compression	Appropriately design or re-dimension compressors
	Reduce anti-surge recycling
	Re-wheel compressors
	Add another train
	Modify pressure levels
	Tune the control system
	Install dry gas seals on compressors
Flaring and Venting	Implement an adequate transportation infrastructure
	Continuously monitor and verify flare, vent and fugitive emissions (e.g. remote-sensing technologies, ultra sonic flow meters)
	Re-route flows sent to vent or flare
	Install a CO_2-capture unit
Heating	Appropriately design and size heating processes
	Promote energy and process integration (heat exchanger network)
	Recover flows, e.g. blanketing gas on equipment or flash drum vapours
	Increase the heat transfer area
	Implement an organic Rankine cycle or a steam Rankine cycle
Cooling	Exploit exergy from cooling of compressed gas and dissipation of cooling water into the sea
Power generation	Electrify the oil and gas platform
	Use energy inputs with low carbon intensity, e.g. hydrogen, wind, biomass, solar
	In the utility plant, replace conventional combustion technologies with combined cycles
	Appropriately design or re-dimension gas turbines
	Compare reciprocating engines and gas turbines
	Use energy efficient turbines
	Reduce hot water in the cogeneration system (TG)
	Explore a bottoming cycle in the gas turbines
	Recover exergy destructed in the valves in the fuel gas system
	Install better metering to improve consumption monitoring
	Select the best share between local and shore power generation
	Optimize the load share between the plant and the gas turbines

Source: The author, 2024

Table A.5 - Field information considered in the analysis (W1)

Parameters	Values	Unit
CO_2	10,00	molar composition - %
C_1	51,29	molar composition - %
C_2	7,07	molar composition - %
C_3	4,87	molar composition - %
C_4	2,89	molar composition - %
C_5	1,45	molar composition - %
C_{6+}	24,02	molar composition - %
Temperature	45,0	ºC
Pressure	29,0	bar
GOR	19,5	%
WOR	9,5	%

C – carbon; C_n – (n) represents the number of C in the oil composition; GOR – gas−oil ratio; WOR – water−oil ratio or water cut or produced water.

Source: The author, 2024

Table A.6 - Compression system configurations (stage 6)

<table>
<tr><td>Module</td><td colspan="6">Compression System</td></tr>
<tr><td>Stage numbers</td><td colspan="6">4 (A, B1, B2, and C)</td></tr>
<tr><td>Share (exported and re-injection)</td><td colspan="6">50% of the natural gas is exported and 50% is re-injected.</td></tr>
<tr><td></td><td>Isentropic efficiency (%)</td><td>k</td><td>c_p (kJ/(kg.K)</td><td>Suction temperature (ºC)</td><td>Suction pressure (bar)</td><td>Discharge pressure (bar)</td></tr>
<tr><td>Group A</td><td>71,43</td><td>1,26</td><td>2,49</td><td>40,0</td><td>14,5</td><td>55,0</td></tr>
<tr><td>Group B1</td><td>70,33 (gas injected)
63,95 (gas exported)</td><td>1,28</td><td>2,39</td><td>40,0</td><td>45,0</td><td>250,0</td></tr>
<tr><td>Group B2</td><td>42,97 (CO_2)</td><td>1,27</td><td>0,90</td><td>40,0</td><td>45,0</td><td>250,0</td></tr>
<tr><td rowspan="2">Group C</td><td>50,88 (gas)</td><td>1,28 (gas)</td><td>2,38 (gas)</td><td>40,0</td><td>250,0</td><td>500,0</td></tr>
<tr><td>28,12 (CO_2)</td><td>1,27 (CO_2)</td><td>0,89 (CO_2)</td><td>---</td><td>---</td><td>---</td></tr>
</table>

k – ratio of specific heat at constant pressure and volume; Cp – specific heat capacity

Source : Based on Barbora *et. al*, 2018

Table A.7 - Indicators defined for monitoring

Type	Indicators	Description	Equations	Unit
Production indicators	Oil production (OP)	Ratio of oil production and fuel consumption	$OP = \dot{m}_o/\dot{m}_f$	dimensionless
	Gas production (GP)	Ratio of gas production/ fuel consumption	$GP = \dot{m}_g/\dot{m}_f$	dimensionless
Power requirements indicators	Thermal demand (TD)	Sum of the thermal demands of the processing plant	$TD = q_o\,\dot{m}_o + q_{CO_2}\,\dot{m}_{CO_2}$	MW
	Electrical demand (ED)	Sum of the electrical demands of the processing plant	$w_p = \frac{v\,\Delta p}{\eta_p};\ w_c = \frac{c_p T_{in} R^{\frac{k-1}{k}-1}}{\eta_c};$ $ED = w_{p,o}\,\dot{m}_o + w_{p,w}\,\dot{m}_w + \sum_{j=1}^{m} w_{c,j}\,\dot{m}_{g,j} + w_{s,g}\,\dot{m}_g$	MW
Energy indicators	Gas turbine efficiency	Obtained from the efficiency curve of the gas turbine, considering the electrical demand	--	%
	Average fuel (treated gas) consumption ($\dot{m}_f$)	Obtained from the efficiency of the gas turbine and electrical energy produced	$\dot{m}_f = \frac{ED}{LHV\,\eta_t}$	kg/s
	Energy efficiency ($\eta_{en,i}$)	Ratio of the desired product - electric and thermal demand - to the spent resources in terms of energy - fuel	$\eta_{en} = \frac{ED + TD}{\dot{m}_f\,LHV}$	%
Exergy indicator	Exergy efficiency ($\eta_{ex,i}$)	Ratio of exergetic demand - electric and thermal exergy demand - to fuel exergy	$BT_o = TD\left(1 - \frac{T_a}{T_o}\right)$ $\eta_{ex} = \frac{ED + BT_o}{\dot{m}_f\,b_f}$	%
Emissions indicator	CO_2 emissions (E_{CO_2})	Ratio of CO_2 emissions to the electric and thermal exergy demand	$BT_{ex} = TD\left(1 - \frac{T_a}{T_{ex}}\right)$ $E_{CO_2} = \frac{\dot{m}_{CO_2,eq}}{(ED + BT_{ex})}$	g/kWh

Source: Based on Barbosa *et al.*, 2018; Sánchez; Oliveira, 2015; Sánchez, 2017.

$\dot{m}_o$ - oil mass flow rate; $\dot{m}_f$ - fuel consumption; $\dot{m}_g$ - gas mass flow rate; $\dot{m}_{CO_2}$ - CO_2 gas mass flow rate;

q_o - separator specific thermal demand; q_{CO_2} - CO_2 separator specific thermal demand;

w_p - pump specific work; v - specific volume; Δp - pressure difference;

η_p - pump efficiency;

w_c - compressor specific work; c_p - specific heat at constant pressure; T_{in} - gas temperature at compressor suction; R - pressure ratio; k - ratio of pressure and volume specific heat; η_c - compressor efficiency;

$w_{p,o}$ - oil pump specific work; $w_{p,w}$ - water pump specific work; $\dot{m}_w$ - water mass flow rate; $w_{c,j}$ - compressor j specific work; $\dot{m}_{g,j}$ - gas (treated, untreated or CO_2) mass flow rate of compressor j; $w_{s,g}$ - main separator specific work;

LHV- low heat value; η_t - gas turbine efficiency;

BT_o - thermal exergy flow rate; T_a - ambient temperature; T_o - heated oil temperature; b_f - fuel specific exergy;

BE_{ex} - thermal exergy flow rate; T_{ex} - exhaust gas temperature; $\dot{m}_{CO_2,eq}$ - CO_2 equivalent emission mass flow rate.

Table A.8 – Thermal and electrical demand per system (in 2019).

Systems	Thermal (MW)	Electrical (MW)			
		Water	Oil	Gas	CO_2
Separation Module					
Separation Train and Vapor Recovery Unit	30,40	0,851			
CO_2 Separation Unit (*) (CO_2 membranes)	0,00	0,00			
Pumps					
Pump Power	---	3,12	7,12	---	---
Compressors					
Group A	---	---	---	13,06	
Group B1	---	---	---	8,96	7,85
Group B2	---	---	---	---	0,99
Group C	---	---	---	4,44	0,61
Total	30,40	47,00			

(*) negligible.

Source: The author, 2024