TOWARDS A LIFETIME EXTENSION STRATEGY FOR CIVIL STRUCTURES

Development of a maturity-based decision making framework for the lifetime extension of civil structures, in the context of the oil and gas industry, civil engineering and asset management.

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- Asset management
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- Lifetime extension
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- Four stage framework
Towards a lifetime extension strategy for civil structures

Development of a maturity-based decision making framework for the lifetime extension of civil structures, in the context of the oil and gas industry, civil engineering and asset management
This report is the result of my MSc thesis project for the education program Construction Management and Engineering at the Delft University of Technology. I have experienced that the MSc program was all about combining the technical, managerial and economic challenges in the construction industry. The concept of lifetime extensions involves combining these challenges and keeping the right wheels turning.

My major inspiration for choosing the subject of lifetime extensions was the renovation project for office spaces that I have supervised in 2011. The original offices were built around 60 years ago, closely after world war II. There was no documentation available about the original offices and the chance was slight that the people who had built the offices were still alive. As result, all kinds of problems arose during the execution of the project. Ever since this project I kept wondering: Why haven’t they invested more during the last 60 years? Why didn’t people put more effort in maintaining the offices? At the same time, dealing with these problems provided a great opportunity to save costs during the new lifecycle of the offices. The dilemma of this lifetime extension kept me fascinated until the end of my MSc program. During the MSc thesis project I learned to understand the concept of a lifetime extension and how the choices are made during a lifespan of a large construction project.

This research would not have been possible without my graduation committee. A special thanks for all the help, support and understanding for the struggles I have faced during the research. Paulien, thank you for challenging me and showing me to reflect critically on my own work. Telli, you really inspired me to learn about theories that were unfamiliar to me and you also really helped me to structure my thoughts. Rob, thank you for the extra effort at the end of the project. I really like that you kept challenging my ideas to test whether I really understood what I was doing. Hans, thank you for the opportunity to get a look inside a major organization as Shell. For me the entire organization seemed like a well-oiled machine and it was hard for me to find anything to improve.

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Nicole Mooibroek
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SUMMARY

The economic lifetime of an asset used for the exploration and processing of oil and gas is strongly influenced by the market. In case of an extended economic lifetime, oil companies often decide to also extend the asset’s technical lifetime. The larger part of the scope of the technical lifetime extension (LE) is determined by civil structures. The problem is that, in the oil and gas industry, maintenance of civil structures is of second-order priority. It is currently difficult to take adequate decisions for the LE, since there is little knowledge about all the influences affecting the civil structure’s lifespan. In this research the decisive influences affecting the civil structure’s lifespan are explored. The insights are used to create a four stage decision making framework for the LE of civil structures in the oil and gas industry, based on the maturity of the civil asset organization.

Situation
Two of the most important sources of energy are oil and gas. During the development of an asset used for the exploration and processing of oil and gas, an estimate of the future return on investment is made. This is strongly influenced by the market. The estimated costs and benefits are used to establish the economic lifetime of the asset. However, due to several external influences, the economic lifetime can be extended over time. In that case, the oil company can decide to extend the asset’s technical lifetime as well. Unfortunately, an technical lifetime extension (LE) cannot be executed without an impact on organizational aspects and additional investments. The larger part of the asset consists of civil structures. Fortunately, civil structures often deteriorate at slow pace and the signs of deterioration are often visible before failure. However, there is also limited attention paid to these kind of systems, because not all the influences on the civil structure’s lifespan are known and priority is given to the systems of direct importance for the production. As result, the majority of technical LE scope includes the work related to civil structures.

The context surrounding the civil structure is determined by the combined influences from the oil and gas industry, asset management and civil engineering. The international oil and gas business is highly competitive, which entails a fast but accurate decision making process to manage the performance of the civil structure. Furthermore, the civil structure cannot be moved to another place to start a new economic life in the case that the gas field is exhausted. Therefore, both the market and the available resources determine the economic lifetime of the civil structure.
Complication
The problem is that maintenance of civil structures in the oil and gas industry is of second-order priority due to systems of direct importance for the production. However, in case of an extension of the economic lifetime, the larger part of the technical scope of the LE is determined by civil structures. In the literature there is a gap between the application of theoretical decision making models for LEs and the practical implications. As result, there is little knowledge about all the influences to consider for a civil structure’s LE, despite the existing theoretical models and frameworks. The current gap of knowledge makes it difficult to take adequate decisions about the lifetime extension interventions that need to be done. Therefore, the research objective is to gain insights into the influences on a civil structure’s lifespan in the oil and gas industry and use these insights to develop a decision making model or framework for LEs that is fit for practice.

Approach
The research is divided in a theoretical part and a practical part. The theoretical part of the research consists of a literature research to identify the external influences from the context, to describe the relationship between system performance and decision making in theory and to design a decision making framework for LEs. The literature research results in the following theoretical framework for the empirical research:

The theoretical framework is approached as a system-of-systems (SoS). An SoS is an assemblage of components which individually may be regarded as systems. The additional properties of these individual system is that these are operational and managerial independent. The current state of the SoS is defined in four stable forms of maturity. The maturity represents the response to the external influences from the context. Using successively an implementing, supporting or driving strategy enables to reach the next maturity level. The strategies can be applied using decision elements, which are the aspects to consider for the asset organization and the LE.

The empirical part of the research consists of an analysis of the results of a questionnaire and a multiple-case study. The decisive influences affecting the decision-making process and the system’s performance are explored. The combined results of the literature and empirical research are transformed into a decision making framework for LEs.
Results of the empirical research
The empirical research resulted in an list of decisive influences, based on past experiences with multiple cases worldwide. The decisive influences on the performance of the civil structure are:

- **Initial design** - The initial design is not fit for purpose for local climate conditions, because of the use of wrong materials.
- **Process effects on materials** - Process effects on materials, as result of weak spots and insufficient attention to details, are underestimated.
- **Focus on low project costs** - Focus on low project costs during the design and execute phase, this is related to the time pressure.
- **Inability of contractor to deliver the quality** - The contractor is unable to deliver the quality as specified by the organization.

The decisive influences affecting the decision making process regarding the civil structure are:

- **Demand and supply of gas** - A change compared to the initial prognosis for the amount of gas is the driver for an LE.
- **New norms and standards** - On the one hand the adoption of new norms and standards provides the possibilities to improve the performance of the system, but on the other hand it leads to a large scope and investment.
- **Knowledge and skills** - There was a lack of knowledge at the sites, due to a continuous change of management, the policy to embed local workforce and the limited experience of the contractors.
- **Technological change** - Some parts of the asset have a shorter design life than other parts. The development of new technologies results in an early replacement of sub systems.

The drivers for success of interventions during the civil structure’s lifespan are:

- **Focus on initial quality** - Identifying the external influences on the system’s performance enables to close the gaps between the initial quality of the system and its operating context.
- **Unique and innovative solutions** – An unique, creative and innovative solution can improve the system performance.
- **Triggers** – Incentives or triggers are needed to avoid postponing, lacking execution or insufficient effort to execute tasks.
- **Resource management** – Using a proper resource management ensures that there is a sufficient amount of spare parts, tools and equipment present to use for the intervention.

The drivers for failure are:

- **Postponing or lacking execution of work** – Postponing or lacking execution of (preventive) maintenance tasks resulted in reactive maintenance.
- **Lack of available knowledge and skills** – A lack of knowledge and skills or a small capacity of the organization resulted in postponing or lacking the execution of the work.
- **Interference** – Interference among different disciplines, or lack of space, leads to inefficient execution of the work. There is a lack of overall view on the LE.

The decisive influences and drivers for success and failures are used to create a four stage decision making framework for the LE of civil structures.
Conclusion
The combined amount of knowledge and skills present in the civil asset organization determines the organization’s current state of maturity. The current state of the can be evaluated using the four stage framework in this research.
Based on the organization’s maturity regarding the present knowledge and skills one can embed knowledge about the influences by:

- Using implementing strategies to mitigate the effects of decisive influences from the context and includes success drivers for interventions.
- Using supporting strategies to create support within the asset organization
- Using driving strategies to enable continuous improvement and to enable other asset organizations (within the business) to benefit from the organization’s knowledge and skills.

The strategies can be used for both the civil asset organization and the LE. Using the strategies for the civil asset organization results in structural changes creating a stable form of maturity for the asset organization. Based on the stable form of maturity, the corresponding LE strategy can be applied, consisting of a set implementing, supporting or driving strategies corresponding with the state of the civil asset organization.

The LE approach varies between a project management approach and a maintenance management approach. For an immature organization a project management approach is needed for the LE. For a mature organization a maintenance approach is used for the LE.

Recommendations
The results of the empirical research are compared with the research assumptions. This resulted in research limitations related to the scope, the data gathering process and the Shell specific context of the research. Therefore, the following aspects need to be examined before implementation:

- It was assumed that the design life of the asset was 20 years. However, there are strong indications that the assumed design life is inaccurate. Therefore it is recommended to make an accurate estimate the actual design life of the assets.
- The system properties were not included in the scope of research. Therefore, it is recommended to include system properties in the framework, align the civil asset master plan with the framework or use the LE scope of the civil asset master plan instead of the decision element ‘focus and priorities’.
- Provide more detailed descriptions of the stages of the four stage framework. In order to do so, it was recommended to examine measurable indicators. These are, for example, the failure and cost reductions per stage.

After the implementation of the framework, it can be used for other sites and disciplines. The civil asset organizations located at the sites should eventually take the lead in using the framework.

In most of the cases the economic life of civil structure in the oil and gas industry turns out to be longer than planned. For civil asset organizations, it is recommended to focus on the 3rd stage of the four stage framework. An internal support is created in this stage, for a preventive response to the influences on the civil structure’s lifespan. As result, the civil asset organization can include the LE in the daily (non-routine) maintenance practices instead of approaching the LE as a project.
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**TERMINOLOGY AND ABBREVIATIONS**

**LE**
(technical) Lifetime extension

**CSO**
Civil Structures and Offshore department (in Shell)

**DUT**
Delft University of Technology

**EAM**
Engineering asset management

**EPC**
Engineering and Procurement Contract

**LNG**
Liquefied natural gas

**OE**
Operational Excellence department (in Shell)

**P&T**
Projects and Technology (in Shell)

**RBI**
Risk-Based Inspection

**RCM**
Reliability Centered Maintenance

**SoS**
System-of-systems

**Civil asset organization**
Organization responsible for the management of civil assets, located at the site

**Civil structure**
Parts of the asset related to steel, concrete, insulation and coatings

**Decision element**
Subject to consider for decision making

**Decisive influence**
Influence from the context that is decisive for a reduction of the system's performance. See: system performance

**Inspections**
Performance measurement of the asset, varying from performing visual inspections to using high-tech tools.

**Interventions**
Repair and maintenance tasks

**System**
In this research: civil structure

**System performance**
The combined reliability, availability and maintainability of the system. See: system
1. INTRODUCTION

Two of the most important sources of energy are oil and gas. According to the scenarios developed by Shell (2013), particularly the exploration of gas is assumed to be increasing until at least 2050.

However, the industry is facing some challenges for the future. Politics and local societies are increasingly affecting the exploration and processing of oil and gas. Besides, the costs and benefits for the oil companies are strongly influenced by the market. A recent example can be found in the current drop of the oil price. Many international and national oil companies have already announced to scale down their investments.

The exploration and processing of oil and gas is done using different types of assets. During the development of the asset, an estimate of the future return on investment is made to establish the economic lifetime. The expected economic lifetime determines the timespan the asset needs to function. This is called the functional or service lifetime of the asset. The asset is then designed in such way that the reliability of the asset is ensured during its functional life.

Several external influences, such as higher demands, higher prices and resource availability, can extend the asset's economic lifetime. For example, the economic lifetime can be longer than planned due to new insights about the amount of gas in the field nearby. In that case, the oil company can decide to extend the technical lifetime as well. Many cases, for example Brunei LNG, Malaysia LNG and the Bacton Gas Terminal, already showed that a technical lifetime extension (LE) was needed. Unfortunately, an LE cannot be executed without an additional investment and an impact on organizational aspects.

The larger part of the investment for the LE is related to civil structures. Civil structures are built to function for a long time, despite the fact that aging of systems comes with deterioration. Fortunately, civil structures often deteriorate at slow pace and the signs of deterioration are already visible before failure. However, there is also limited attention paid to these kinds of systems, because not all the influences on the civil structure's lifespan are known and priority is given to the systems of direct importance for the production. As a result, the majority of technical LE scope includes the work related to civil structures.

The challenges, such as politics and the market, affect the civil structure's lifespan. However, there are also many unknown external influences affecting this lifespan. More knowledge about the influences on the civil structure's lifespan is needed to decide about the aspects to consider for the LE.

The specific context surrounding the civil structure is explained in section 1.1. After that, the problem and desired situation of LEs will be explained more in detail in section 1.2. In section 1.1.3 the relevance for the organization involved in the research is discussed.
1.1 The context

The context is delineated through the influences from (1) the oil and gas industry, (2) asset management and (3) civil engineering. The relationship between aspects is presented in Figure 1-1, in which the context is delineated through the overlapping fields of knowledge. The challenges deriving from the context will be elaborated in sections 1.1.1. and 1.1.2.

![Figure 1-1: Delineation of the context](image)

1.1.1 Engineering asset management in the oil and gas industry

Civil structures are (interrelated) assets owned by a single person or organization. An asset can be defined as an item, thing or entity that has potential or actual value to an organization (ISO, 2014). Individual assets are interrelated and can only contribute value in a systems context. Management of these asset systems involves the balancing of costs, opportunities and risks against the desired performance of assets, to achieve the organizational objectives (ISO, 2014).

Engineering asset management (EAM) can be defined as ‘the management of physical, as opposed to financial, assets’ (Amadi-Echendu et al., 2010). During the last decades the theories developed on optimal EAM are not often put into practice. EAM includes making decisions about the physical asset. However, decision-making is concerned with many different influences and these influences can also differ per moment of time. Therefore, it can be stated that applying theoretical models is hardly possible due to the uniqueness of each situation.

The decision-making process in the oil and gas industry requires speed, because the international oil and gas business is highly competitive. At the same time, the (process) safety within these companies is of such importance that little risk can be taken. Therefore, the management of assets in the oil and gas industry entails a fast but accurate decision-making process.

1.1.2 Managing civil structures in the oil and gas industry

In the oil and gas industry, the larger part of the engineering asset systems are civil structures. The scope of civil engineering includes the work related to steel, concrete, insulation and coatings. Maintaining these aspects is often of second-order priority, because priority is given to systems of vital importance for the production, such as rotating equipment and IT-systems. There is also limited knowledge about all the influences on the civil structures lifespan. Therefore, the people responsible for civil structures face difficulties in decision-making regarding the maintenance, repair and inspection practices. In this research, the actions related to maintenance and repair are defined as the interventions in the civil structure's lifespan.

There are certain limitations for civil structures (attached to the subsoil) in the oil and gas industry. For example, floating assets can be moved from one place to another. A new
economic lifetime can be started at another location in case the current gas field is exhausted. This is impossible for an onshore civil structure. Therefore, the economic lifetime is decisive. The approach to the lifecycle of civil structures owned by oil companies differs from the approach to civil structures owned by public organizations. For example, roads and bridges owned by public organizations can have a functional life of more than 100 years. The main driver for the lifetime of these civil structures is the public value, while for civil structures in the oil and gas industry the main drivers are the market and the available resources.

1.1.3 Relevance of the research

This research is conducted as a joint project of the Delft University of Technology (DUT) and the Civil Structures and Offshore (CSO) department of Shell Global Solution International BV (hereafter: Shell). The research has relevance for both organizations. For Shell this research is relevant because CSO is responsible for the (engineering) support in civil asset management in the oil and gas industry. Currently there is little knowledge present about all the aspects to consider for an LE. The research provides possibility to learn from existing theories and get more control on the civil asset management practices. The insights are relevant for the DUT because there is a need for more theoretical and practical information on the topic of EAM. Theories on EAM are not often put into practice. EAM as a research area has received more and more attention during the last decades, since a lot of structures are aging. New insight into the influences to consider for an LE, as well as the practical implications of LEs will provide more knowledge for the further development of theories on EAM decision-making. Many civil assets were built decades ago. This applies not only to oil and gas facilities, but also to roads, bridges, railways, buildings and similar types of constructions. EAM decision-making is also concerned with these types of assets. The insights gained in this research can be used to as a starting point for similar researches focused on an asset’s LE in other industries.

1.2 The problem of lifetime extensions

This section will focus on the problem of LEs for civil structures in the oil and gas industry. The economic lifetime of the civil structures is determined by the available resources and the market. Due to changing external demands, such as a long-term increase of energy consumption, the civil structures have a longer economic lifetime than its technical lifetime. Therefore, a technical LE of the civil structure is needed. In section 1.2.1, the problem definition for this research is provided. After that, in section 1.2.2 the research objective and research questions established. In order to reach the desired situation, the method to answer the research questions is shortly discussed in section 1.2.3.

1.2.1 Problem definition

Maintenance of civil structures in the oil and gas industry is of second-order priority. However, in case of an extension of the economic lifetime, the larger part of the technical scope of the LE is determined by civil structures. Insights about the extended economic lifetime can be gained during each stadium of the system’s lifespan, also when the technical lifetime is almost finished. Due to the uniqueness of the situation, an LE cannot be considered as a set of standard maintenance tasks. An LE can neither be considered as a new built or Greenfield project, because the system already exists. In this research, the LE is defined as a project-based scope definition and a maintenance-based approach.
In the literature there is a gap between the application of theoretical decision-making models for LEs and the practical implications (Dekker, 1996, pp. 235-236; Rausand, 1998, p. 130). Many theoretical and mathematical models (see Niu, Yang, and Pecht (2010); Van Horenbeek and Pintelon (2013); Yssaad, Khiat, and Chaker (2014)) are made to predict the interventions needed for a system’s LE. However, most of the decision-making models are not adjusted towards real life practices and do not include all external and internal influences on the system’s lifecycle. Besides, the variety and context-specific nature of the existing methods makes the establishment and application of formal guidelines fairly complicated (Korpi & Ala-Risku, 2008, p. 255). This leads to the following problem definition:

There is little knowledge about all the influences to consider for a civil structure’s LE, despite the existing theoretical models and frameworks. This gap of knowledge makes it difficult to take adequate decisions about the lifetime extension interventions that need to be done.

1.2.2 Research objective and central question

The existing decision-making methods for an LE are limited by the context specific nature and a lack of connection to practice. More insight into the context of civil structures in the oil and gas industry, as well as the existing decision-making methods will provide insight into the decisions needed to successfully extend the civil structure’s lifespan. This leads to the following research objective:

To gain insights into the influences on a civil structure’s lifespan in the oil and gas industry and use these insights to develop a fit-for-practice decision-making model or framework for lifetime extensions.

Insights into the external influences from the context on the civil structure’s lifespan provide the possibility to steer the decision-making process. This way, the potential negative effects can be limited for the next lifespan. An organization can then focus on maintaining the civil structure at sufficient quality level within reasonable budgets. When the system’s performance is maintained at an organization’s desired level, the knowledge gained about the ‘how to’s’ can be used to extend the technical lifespan of the civil structure. This leads to the following central question for this research:

How can knowledge about the influences on a civil structure’s lifespan be embedded in the decision-making process for a lifetime extension?

In this research, the civil structure is seen as a system. The reliability, availability and maintainability of the system during its lifespan is represented by the system’s performance. Insight into the influences affecting the system performance and the decision-making process enables to answer the central question. Therefore, a set of sub questions are defined. The sub questions will be answered throughout the research using a literature research and an empirical research.
Based on the literature research the following sub question is answered:  
A. What kind of influences from the context can be found in the literature?

The influences identified by the literature research are validated through the empirical research. The following sub questions will be answered:  
B. What are the decisive influences affecting system performance?  
C. What are the decisive influences affecting the decision-making process?  
D. What are the drivers determining the success of inspections and interventions?

Based on the combined results of the literature research and the empirical research the following sub questions will be answered:  
E. How can the success drivers and decisive influences be embedded into the decision-making process to maintain the system's performance?  
F. What are the possible strategies for a lifetime extension?  
G. How can the relationship between system performance and the decision-making process be described?

1.2.3 Method  
In order to give answer to the research questions, the research is divided in a theoretical part and a practical part. The theoretical part of the research consists of a literature research to identify the external influences from the context, to describe the relationship between system performance and decision-making in theory and to design a decision-making framework for LEs.  
The practical part of the research consists of an analysis of the results of a questionnaire and a multiple-case study. These are used to establish the decisive influences on the civil structure's lifespan.  
The combined results of the literature and empirical research are transformed into a decision-making framework for LEs. This framework includes the possible strategies for LEs. The framework is verified through expert interviews and validated by applying the framework to a case and by evaluating the research findings. The latter enables to describe the relationship between system performance and decision-making from both the theoretical and practical point of view.  

1.3 Thesis outline  
This research will focus on LEs, within the context of the oil and gas industry, civil engineering and asset management. This subject was introduced in this chapter. Figure 1-2 shows the structure of the rest of the thesis.

FIGURE 1-2: STRUCTURE OF THIS THESIS

The next chapters, Chapters 2 and 3, are based on findings from literature. First, identified gaps between theory and practice are described, but also the dependent and independent
variables within this research are identified. This will lead to a theoretical framework as a basis for the rest of the research. After that the theoretical framework is operationalized, so that it can be used as a boundary for the practical research.

Chapters 4 and 5 are based on findings from practice. An exploratory and explanatory research is done to explain the occurrence of influences within the theoretical framework. This will result in a decision-making framework and strategies for a LE.

In Chapter 6 the decision-making framework is applied to a case and reviewed by experts. The last chapter, Chapter 7, will be used to give answers to the research questions, and also to provide steering for theory and practice in the future.
2. THEORETICAL CONTEXT: EXPLORING THE GAP OF KNOWLEDGE

There are gaps between the models developed in theory and the implications in practice. This chapter will focus on these gaps and different theories provided in the literature to decrease these gaps. The following research questions will be discussed:

A. What kind of influences from the context can be found in the literature?
G. How can the relationship between system performance and the decision-making process be described?

First, the gaps of knowledge are identified to develop a conceptual model. The conceptual model is a visual representation of all assumed relationships between the variables within this research. The conceptual model is used to explore the remaining knowledge gaps more in depth in the rest of the chapter. The chapter will be concluded with the theoretical framework that will be used in the rest of the research.

2.1 Gap between theory and practice

There is a gap between theory and practice, but the causes of the gap are still unknown. If it is possible to find out where the gap originates from, it might be possible to decrease or even close this gap. Section 2.1.1 identifies the cause of the gap between theory and practice.

The knowledge gained about this cause is to develop a conceptual model including the assumptions for this research, in section 2.1.2.

2.1.1 Cause of the gap

Several decision-making models for optimization of maintenance can be found in the literature, but most of them are only usable for theoretical purposes. Dekker (1996, p. 235) states that these models are focused on mathematical analysis and techniques, rather than solutions to real problems. He also argues that, because of their stochastic nature, these models are difficult to understand and to interpret. In addition, Van Horenbeek, Pintelon, and Muchiri (2010, p. 190) explain that these models are limited to very specific problems and that not all optimization criteria are included in these models.

The theoretical and mathematical approach of the existing models results in limited connection to the practical implications for industries, because little attention is paid to the applicability of the models (Scarf, 1997, p. 494). Furthermore, practitioners have little knowledge of which models are suited for which specific problem (Dekker, 1996; Van
Horenbeek et al., 2010). This is acknowledged by Wang (2002, p. 470), who states that there is a limited number of maintenance policies which all maintenance models can be based on. Rausand and Høyland (2004) state that a mathematical model is necessary, but there are two conflicting interests. These are, on the one hand, that the model should be sufficiently simple to be handled by available mathematical and statistical methods. On the other hand the model should be sufficiently “realistic” such that the deducted results are of practical relevance.

In practice, traditional maintenance plans are often based on a combination of recommendations from manufacturers, legislation and company standards, and – to a minor extent – maintenance models and data. However, these recommendations from manufacturers are not always based on real experience data (Rausand, 1998, p. 121). There is a need to find opportunities to close the gap between theoretical models and practical problems. Scarf (1997), Dekker (1996) and also Jardine, Lin, and Banjevic (2006) mention ‘data’ as one of the improvements for the applicability of these models. This involves the quality, amount and storage of (real life) data used for the models. In addition, Jardine et al. (2006, p. 1500) mention the following areas of improvement to implement maintenance technologies in the industry:

- Communication between theory developers and practitioners in the area of reliability and maintenance,
- Efficient validation approaches,
- The difficulty of implementation due to frequent change of design, technologies, business policies and management executives,

It can be argued that these three improvements are related to the use of real life data to theoretical models. Therefore, the main focus of this research is on the use of real life data to develop a theoretical model.

### 2.1.2 Conceptual model and its assumptions

The use of real life data in theoretical models provide the possibility to decrease the gap of knowledge. A conceptual model (Verschuren, Doorewaard, & Mellion, 2010) is developed to identify the real life data needed. The conceptual model, shown in Figure 2-1, provides an overview of the assumed relationships between the variables for this research. The main assumption is that there is a mechanism of two dependent main variables, which are (1) decision-making and (2) system performance. Both the variables ‘decision-making’ and ‘system performance’ are influenced by the context and the variables are influencing each other through the mediator variables (3) interventions and (4) inspections. More specific, the system’s current state or performance is affected by influences from the context, such as climate conditions and the interventions taken, such as the applied maintenance work. The system performance determines whether or not an inspection should be done. The result of the inspection influences the decision-making process, but the decision-making process also determines whether the inspections is carried out. At the same time, there are also influences from the context affecting the decision-making process, such as competition from other companies.

Concluding, the decision-making process indirectly influences system performance through interventions. The effectiveness of the interventions directly influences system performance. This implies that changing system performance starts with changing the decision-making process for the interventions to be taken.
Steering the decision-making process into a certain direction entails a clear overview of the relationship between all variables. This can be done with the use of systems thinking, in which the focus lies on 'the whole system or organism', as explained by Nicholas and Steyn (2012, pp. 46-47). In this approach, the system is considered as a whole, while at the same time the relationship between the parts, or variables, is considered.

When considering the conceptual model as a whole or total system, the specific gaps of knowledge can be structured into more specific topics. This leads to three kinds of gaps that will be explored more in depth in the remaining part of this chapter. As shown in Figure 2-1, the gaps to be explored are (1) the influences from the context on the total system, (2) the relationship between the variables and the entire system and (3) the input needed to reach the desired output or, in other words, the realization of a LE. These three gaps will be explored more in depth in the next three sections.

2.2 The context

Each system operates in a specific context, but it is often difficult to identify what the specific influences from the context are. This section explores the influences from the context already identified by other researchers. First, the external influences on the system's performance are explored in section 2.2.1. After that, the external influences on decision-making processes are discussed in section 2.2.2. The insights will be used to extend the conceptual model to a theoretical framework as input for the practical part of this research.

2.2.1 External influences on system performance

During a system's lifespan there are influences from the context causing failures. The external influences are identified through a literature review. The review is done within several kinds of industries to match the pattern of overlap. The findings are analyzed hereafter.
Wijnia (2012) provides an overview of the categories of the risk process for energy distribution infrastructures. Most of the causes mentioned can be directly related to system performance, the other causes mentioned are related to interventions or the decision-making process. These are (1) deliberate damage, (2) accidents, (3) acts of god, (4) systemic faults and (5) change in environment.

The Nuclear Energy Agency (2012) mentions (1) the state of other components, (2) abnormal environmental stress, (3) internal to component and (4) coupling factors, as factors that can influence system performance. Lastly, the category ‘unknown’ causes is mentioned, which can be used when the cause of the component state cannot be identified.

Shell (2014a) provides a best practice guideline for lifetime extension of civil structures, based on experience. Within this guideline the factors (1) change in environmental loads, (2) degradation due to environmental deterioration process, (3) visible deterioration patterns and (4) corrosion/erosion life, are mentioned.

The insights mentioned above lead to four main categories of external influences, which are (1) deliberate damage, (2) accidents, (3) environmental effects, (4) process specific effects and (5) design and construction errors. The latter includes the effects of processing oil or gas. An overview of these categories can be found in Table 2-1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Deliberate damage</th>
<th>Accidents</th>
<th>Environmental effects</th>
<th>Process-specific effects</th>
<th>Design and construction errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wijnia (2012)</td>
<td>deliberate damage</td>
<td>Accidents</td>
<td>Acts of god</td>
<td>Systemic fault</td>
<td>Asset flaws</td>
<td></td>
</tr>
<tr>
<td>Nuclear Energy Agency (2012)</td>
<td></td>
<td>Abnormal environmental stress</td>
<td>Internal to component, piece part</td>
<td>Design, manufacture or construction inadequacy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell (2014)</td>
<td>Change in environmental loads</td>
<td>End of useful fatigue life</td>
<td>Absence of visible deterioration patterns</td>
<td>End of corrosion/erosion life</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2.2 External influences on decision-making

Decision-making processes are also influenced by the context. The context includes the social, cultural, economic and physical environments, as well as regulatory, financial and other constraints (ISO, 2014). Also for the decision-making process the external influences are identified through a literature review. The review is done within several kinds of industries to match the pattern of overlap. The findings are analyzed hereafter.

Liyanage (2012) mentions the factors (1) clear policies and procedures, (2) power of societies, (3) global trends, (4) dynamics of competition, (5) demands and (6) knowledge.

The overview provided by Wijnia (2012) shows two categories of risks, which can be categorized as external influences on the decision-making process. These causes are (1) change institutional environment and (2) change of requirements.

Within the best practice guideline the factors (1) civil expertise present at location and (2) budget allocation and priority are mentioned.

Two other important causes are provided in the literature. Schuman and Brent (2005) mention the factor human reliability, which includes the level of involvement in
maintenance plans and whether the decision maker has ownership of the operated asset. The other cause is a combination of the factors (1) economic lifecycle, (2) return on investment and (3) shareholders’ profit, mentioned by Komonen (2012).

Demirel and Hertogh (2014) mention nine categories of factors influencing the road network sector. Eight of these categories have some overlap with the categorization of external influences on the decision-making process within this research. These categories are (1) change in regulations, (2) change of requirements, (3) change in politics, (4) change in resources, (5) market change, (6) organizational change, (7) financial change and (8) technological change. The latter includes, for example, the use of new materials and techniques.

The categories for the external influences as result of the literature review are (1) norms and regulations, (2) local aspects, (3) demand and supply, (4) knowledge, (5) management, (6) costs and (7) technological change.

Table 2-2 provides an overview of the categorization of the above mentioned factors.

<table>
<thead>
<tr>
<th>Category Source</th>
<th>Norms /Regulations</th>
<th>Local aspects</th>
<th>Demand /Supply</th>
<th>Knowledge</th>
<th>Management</th>
<th>Costs</th>
<th>Technological change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wijnia (2012)</td>
<td>Change institutional environment</td>
<td>Change requirements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell (2014)</td>
<td></td>
<td></td>
<td>Change requirements</td>
<td>Civil expertise present at location</td>
<td>Budget allocation / priorities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schuman and Brent (2005)</td>
<td>Clear policies and procedures</td>
<td>Power of societies</td>
<td>Demands</td>
<td>Knowledge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liyanage (2012)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Komonen (2012)</td>
<td>Change in Regulations</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Demirel and Hertogh (2014)</td>
<td>Change in Regulations</td>
<td>Change in Politics</td>
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</tbody>
</table>
2.3 Systems and systems-of-systems

The influences from the context affecting the whole system are identified, but it is still unknown how the whole system functions. This section will provide background on the functioning of systems and system-of-systems. Furthermore, the relationship between the variables in this research as parts of the whole system will be explained.

2.3.1 General systems theory

As explained in section 2.1, the conceptual model is approached as a system. This way of thinking originates from the General Systems Theory, which has come into use to describe a level of theoretical model-building that lies somewhere between the highly generalized constructions of pure mathematics and the specific theories of the specialized disciplines (Boulding, 1956, pp. 197-208). The theory studies all thinkable relationships abstracted from any concrete situation or body of empirical knowledge. Sterman (2002) explains systems-thinking as ‘the ability to see the world as a complex system, to understand how everything is connected to everything else’. The theory is used to develop a framework of general theory to enable specialists to catch relevant communications from others.

Using the theory enables to explain the principle of a system and its functioning. Nicholas and Steyn (2012) define a system as ‘an assemblage of things or parts interacting in coordinated way’. This definition is in line with the explanations provided by Boulding (1956) and Sterman (2002). The aspect of interacting corresponds with the aspects ‘relationships’ and ‘connected’. However, there are more characteristics of a system. Naughton and Peters (1976) provide the following characteristics:

- Parts of the system affect the system and are affected by it,
- The assemblage of parts does something; it serves a purpose or goal,
- The assemblage is of particular interest.

With regard to the conceptual model, the variables are seen as the ‘parts’ of the system. The purpose of this system is to provide a lifetime extension of the variable ‘system performance’. However, this variable can also be seen as a system on its own, because all of the above mentioned characteristics can be applied to the variable. The same goes for the variable ‘decision-making’. This principle is called a system-of-systems and will be discussed in the next section.

2.3.2 Systems-of-systems

Maier (1998) states that a system-of-systems (SoS) is an assemblage of components, which individually may be regarded as systems and possesses two additional properties:

- **Operational Independence of the Components**: If the SoS is disassembled into its component systems the component systems must be able to usefully operate independently. That is, the components fulfill customer-operator purposes on their own.
- **Managerial Independence of the Components**: The component systems not only can operate independently, they do operate independently. The component systems are separately acquired and integrated but maintain a continuing operational existence independent from the SoS.

In this research, both the variable ‘system performance’ and ‘decision-making’ satisfy the above mentioned properties. Therefore, the conceptual model is an SoS. Maier (1998) explains that one of the design heuristics for an SoS is to seek stable intermediate forms. The main requirement for improving the performance of the SoS is to structure the improvements in such way that the intermediate forms of the SoS are stable. In that case the decisions made will enable a stable balance between the decision-making process and system performance. The structure will be created in the next section.
2.4 Steering the decision-making process for LEs

Insights into the functioning of the SoS and the influences from its context provides the possibility to steer the decision-making process. This section’s goal is to create stable forms of the SoS that enables an LE through the decision-making process. There are three basic aspects needed for decision-making (Howard, 1968). These are (1) uncertainty, (2) structure and (3) preference.

The first aspect, uncertainty, is expressed by an estimation of the probability that a certain event will occur. In this research the events are the influences from the context, which were identified in section 2.2. The second aspect, structuring, includes combining all variables into a decision problem. The structure for this research entails the inclusion of all influences into the decision-making process for LEs. This is discussed in section 2.4.1. The last aspect, preference, includes, for example, value, time, risks, performance and expected utility. Since this research is focused on LEs, the preferences are related to restoring the system’s performance to an acceptable level, defined by the organization. The preferences are expressed through the combined results of the literature research and the empirical research. The results of the literature research are discussed in section 2.4.2. The structure, together with the preferences, lead to the design of a four stage framework in section 2.4.3.

2.4.1 Structuring the decision-making process

In the literature there are multiple models developed to structure the decision problem in a quantitative or qualitative way. As concluded in section 2.1, these models are less focused towards real problems, difficult to understand, interpret and limited to specific problems. Besides, there is no attention paid to which criteria are important in specific business cases (Van Horenbeek et al., 2010, p. 194).

In practice, the existing decision-making tools are often already embedded in the organization. The models created with these tools are focused on real problems, but are case specific. Therefore, the structure created for the decision-making process for LEs is required to be independent from the tools and methods that are currently used in the organization, while at the same time easy to understand and applicable in multiple cases.

The decision to extend the system’s lifespan depends on the current state of the asset organization’s SoS, which can differ per case. For example, corrective measures were taken during the system’s lifespan in an organization. This implies that the current state of the SoS is less controlled than an organization that has gained more insights into the system’s causes of failure and is able to apply preventive measures.

Defining the different states of the SoS can help to evaluate the relationship between the decision-making process and the system’s performance. The LE strategies can then be adjusted to the current state of this relationship. The different states can be defined using maturity models. Many maturity models in the literature originate from the capability maturity model (CMM) for software. The CMM describes essential attributes that would be expected to characterize an organization at a particular maturity level (M. Paulk, 1993).

The following stages of maturity are described:
1. Initial - Ad hoc, and occasionally even chaotic.
2. Repeatable - Basic project management processes are established to track cost, schedule, and functionality.
3. Defined - The process is documented, standardized, and integrated into a standard process for the organization.
4. Managed - Detailed measures of the process and product quality are collected.
5. Optimizing - Continuous process improvement is enabled by quantitative feedback from the process and from piloting innovative ideas and technologies.
This type of maturity framework has also found its application in other industries. Kerzner (2002) developed the project management maturity model (PMMM), Campbell et al. (2011) developed a maturity framework for asset management and Volker, Van der Lei, and Ligtvoet (2011) developed a similar framework for infrastructure called the infrastructure management maturity model (IM3). It can be assumed that this type of framework is fit for practice, since it is used in these different industries.

The concept of maturity implies that an organization can 'learn'. The levels are defined to reach the an 'aware' and 'capable' state on the asset information (Campbell et al., 2011). Maslow (1954) defines four stages of a learning process. These are:

1. **Unconscious – Incompetence** (*Dutch: Onbewust-Onbekwaam*): The person is not aware of failures.
2. **Conscious – Incompetence** (*Dutch: Bewust-Onbekwaam*): The person is aware of the failure, but not able to avoid the failure from happening.
3. **Conscious – Competence** (*Dutch: Bewust-Bekwaam*): The person is able to avoid the failure.
4. **Unconscious – Competence** (*Dutch: Onbewust-Bekwaam*): The person has repeatedly avoided the failure and is able to function in an auto-pilot mode.

The learning process shows many similarities with the four stage framework for manufacturing processes developed by Hayes and Wheelwright (1984). The framework, shown in Figure 2-2, enables to focus on a long term period of time and decide on the priorities per stage. In the framework the manufacturing strategy can be neutral or supportive to the business objectives. This can be done with an internal or external focus, meaning that the strategy is focused towards the internal practices in relation to the context.

![Figure 2-2: Four-Stage Framework of Manufacturing Strategy Effectiveness, Adapted from Hayes and Wheelwright (1984)](image)

A comparison between the different frameworks shows that the learning process and the framework for manufacturing processes mature when reaching a certain level of awareness and capability to respond to failures, while CMM is focused on the process maturity (M. C. Paulk, Konrad, & Garcia, 1995). However, Bach (1994) states that the CMM ignores the people involved, which implies that the available knowledge and skills are not considered. The learning process of Maslow (1954), on the other hand, matures with the amount of knowledge about certain failures and skills to respond to the failures. The four stages can be supported by strategies to reach the next stage of maturity using the framework developed by Hayes and Wheelwright (1984). Since the SoS includes the decisions made and the inspections and interventions done by people involved, it can be stated that it is more...
relevant for this research to build further on the four stages of both the learning process and the framework of Hayes and Wheelwright (1984).

The four stage framework developed by Hayes and Wheelwright (1984) was adjusted towards maintenance practices by Pintelon, Pinjala, and Vereecke (2006). The framework is used to evaluate the effectiveness of a given maintenance strategy. Table 2-3 shows the current state of each stage as defined by Maslow (1954) and Hayes and Wheelwright (1984). The description of Pintelon et al. (2006) functions as a guide to define each stage of the SoS for LEs, since maintenance practices are more similar to the practices of an LE compared to manufacturing.

<table>
<thead>
<tr>
<th>Current state of the stages</th>
<th>Description</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaware of failures</td>
<td>Minimize maintenance’s negative potential</td>
<td>Corrective measures are taken to respond to all influences</td>
</tr>
<tr>
<td>Aware of failures</td>
<td>Achieve parity (neutrality) with competitors</td>
<td>Decisive influences are known, preventive measures can be taken</td>
</tr>
<tr>
<td>Aware, capable to avoid failures</td>
<td>Provide support to manufacturing and business strategy</td>
<td>The SoS is able to function without the decisive influences affecting it</td>
</tr>
<tr>
<td>Auto-pilot</td>
<td>Promote both maintenance and manufacturing-based competitive advantage</td>
<td>The SoS benefits from its context, a specific LE is not needed</td>
</tr>
</tbody>
</table>

Regarding the current state of each stage, Maslow (1954) states that the optimum lies at the point when someone can perform his or her tasks in an autopilot-mode, while Hayes and Wheelwright (1984) show that a certain awareness is needed to improve the current practices. The latter enables to actively steer on the organization’s advantages related to the context. Therefore, the four stages of the framework for this research are focused toward reaching the externally supportive state in which one is aware and capable to benefit from the context.

The next section will focus on the aspects to make decisions about to reach the next stage and the LE in the context of the organization.

### 2.4.2 Preferences: Quality and effectiveness of actions

In this section the preferences for the management of civil structures are discussed. The interventions need to be effective, so that the system’s performance is restored to the organization’s desired level. In the literature there are different perceptions on how to evaluate maintenance effectiveness. Pham and Wang (1996, p. 426) for example, argue that maintenance can be classified according to the degree to which the operating conditions of an item are restored. However, this classification does not indicate how these actions are executed and why these actions are effective.

Pintelon et al. (2006) state that the effectiveness of maintenance can be known if one is able to identify and evaluate a given maintenance strategy. They evaluate on different maintenance strategies provided in literature (Cholasuke, Bhardwa, & Antony, 2004; Kelly,
1997; Tsang, 2002) and define a set of decision elements, based on the manufacturing strategy elements of Hayes and Wheelwright (1984). In the author's point of view, the approach provides more understanding of an action's effectiveness, compared to Pham and Wang (1996, p. 426). The set of decision elements defined by Pintelon et al. (2006) are distinguished by structural and infrastructural decision elements. Structural decision elements are fixed and related to the organization, for example the facilities present at the site. Infrastructural decision elements are seen as maintenance management elements, such as a performance measurement system. An overview of maintenance decision elements is shown in Table 2-4.

The decision elements are focused on a maintenance strategy, but not on an LE strategy in particular. Since there is little known about the aspects to consider for an LE, the empirical part of this research will focus on the specific decision elements needed for LE. In the resulting four stage framework the structural decision elements are related to the asset organization. The infrastructural decision elements for maintenance management element correspond with the LE. The four stage framework used in this research is designed in the next section.

2.4.3 Four-stage framework design
Steering the decision-making process in the SoS entails the inclusion of uncertainty, structure and preferences in the decision-making process. The proposed design for the four stage framework aims to include these aspects. The structure is developed by the definition of the four stages and a definition of the actual state of the SoS per stage. The preferences are included through the decision elements for the asset organization, as well as the decision elements for the LE. The aspect of uncertainty is dealt with by the strategy per decision element to arrive at the next maturity level. Table 2-5 shows the four stage framework design.
### TABLE 2-5: DESIGN OF THE FOUR STAGE FRAMEWORK FOR LIFETIME EXTENSIONS

<table>
<thead>
<tr>
<th>Type of strategy</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State of the SoS</strong></td>
<td>Corrective measures are taken to respond to all influences</td>
<td>Implementing strategy</td>
<td>Supporting strategy</td>
<td>Driving Strategy</td>
</tr>
<tr>
<td><strong>Decision elements</strong></td>
<td>Decisive influences are known, preventive measures are taken to respond to all influences</td>
<td>Decisive influences are known, preventive measures are taken to respond to all influences</td>
<td>The SoS is able to function without the decisive influences affecting it</td>
<td>The SoS benefits from decisive influences and a specific LE is not needed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Asset organization decision elements</th>
<th>Strategy for improvement</th>
<th>Strategy for improvement</th>
<th>Strategy for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of situation</td>
<td>Description of new situation</td>
<td>Description of new situation</td>
<td>Description of best situation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LE decision elements</th>
<th>Strategy for improvement</th>
<th>Strategy for improvement</th>
<th>Strategy for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of situation</td>
<td>Description of new situation</td>
<td>Description of new situation</td>
<td>Description of best situation</td>
</tr>
</tbody>
</table>

The designed four stage framework is aimed to be applied in multiple situations, depending on the current state of the asset organization’s SoS. The current state of the asset organization determines the LE strategy needed. The empirical part of the research will provide the contents of the framework regarding the decision elements, as well as the strategies and descriptions of the current state for each decision element.
2.5 Sub conclusions

In this chapter the external influences from the context affecting both the decision-making process and the system performance are explored. As result of the literature research, the current knowledge gaps and the empirical research needed to close the gaps, are identified. The research questions provided in the beginning of the chapter are answered in this section.

How can the relationship between system performance and the decision-making process be described?
The decision-making process is influencing the system performance through the mediator ‘interventions’. The system performance is influencing the decision-making process through the mediator ‘inspections’. The inspections are also influenced by the decisions made.

Relationships within the SoS – The relationship between the variables and the total system can be described through the concept of an SoS. An SoS is an assemblage of components which individually may be regarded as systems. The additional properties of these individual system is that these are operational independent and managerial independent. The decision-making process needs to be structured in such way that enables an LE. A mature relationship between the decision-making process and the system’s performance can be created by the definition of stable intermediate forms of the SoS. There are four stages of stable forms of the SoS. The implementing, supporting and driving strategies are used to arrive at the next stage of maturity. The four stages are defined as:
1. Corrective measures are taken to respond to all influences.
2. Implementing strategy, resulting in that the decisive influences on the SoS are known and preventive measures are taken to respond to the influences.
3. Supporting strategy, resulting in that the SoS is able to function without any effect of decisive influences.
4. Driving strategy, resulting in that the SoS benefits from its context.

The relationship between the decision-making process and the system’s performance matures in each stage. In the final stage, one is aware of failures and the external influences and capable using the knowledge to support other asset organizations.

Decisions needed for an LE – The decisions for the LE depend on the current state of the civil asset organization’s SoS. There are decision elements used to define the maturity stage of the asset organization. Decision elements are subjects to make decisions about. The decision elements for an organization are rather structural of nature, cannot be changed easily and are focused on the long-term. For the LE the decision elements are more flexible. The decision elements can be used to align a short-term event with the current state of the organization.

What kind of influences from the context can be found in the literature?
The variables ‘system performance’ and ‘decision-making’ are both directly influenced by the context. The influences on system performance are placed in the following categories:
- *Deliberate damage* - Failure as result of deliberate human actions.
- *Accidents* - Failure as result of unknown influences.
- *Environmental effects* – Failure as result of local climate conditions
- *Process specific effects* – Failure as result of the exploration or processing of oil or gas.
- *Design and construction errors* – Failure as result errors that arose during the construction of the systems.
The influences from the context on decision-making are placed in the following categories:

- **Norms and regulations** – Changes as result of, for example, new industry standards.
- **Local aspects** – Changes as result of the demands of the people and animals living nearby the system.
- **Demand and supply** – Changes as result of the market and the state of the spares, tools equipment.
- **Knowledge** – Changes as result of the amount of expertise present at the site.
- **Management** – Organizational changes.
- **Costs** – Changes as result of the return on investment.
- **Technological change** – Change as result of the development of new technologies.

With these conclusions, the conceptual model can be described as a theory-based SoS, shown in Figure 2-3. The theory-based SoS will function as a guide through the empirical part of the research and will be completed with insights from practice.

The theory-based SoS provides an overview of the influences to be considered in this research. However, there are still some remaining gaps that could not be resolved by the literature research. Therefore, an empirical research is done to close the remaining gaps. The focus lies, first of all, on the external influences from the context. These influences are identified, but the decisive influences that affect the SoS need to be explored further. Second of all, the quality of inspections and effectiveness of interventions needs to be found in practice, since these cannot be abstracted from literature. Third of all, the decision elements for the asset organization and the LE will be derived from the empirical research, since the preferences from practice are needed. After the empirical research is done, it will be possible to define lifetime extension strategies that are at the same time fit for practice. The next chapter describes the methodology used to close the gaps.
In this chapter the theoretical framework is operationalized into a practical research. This is done by:

- An explorative study to identify decisive external influences and key drivers in the SoS, by means of a questionnaire;
- An explanatory study to describe why certain phenomena occur, by means of an embedded multiple-case study;
- An explanatory study to explain how decisive external influences and drivers in the SoS can be embedded in the decision-making process, using the four stage framework.

In the following section the process of the research is explained. The remaining sections will provide a more in-depth explanation of how the above described methods are used.

3.1 Research process

Some ground rules for the research are established to answer the research questions. The ground rules are discussed in this section. First, a process design is made to structure the research. After that, four tests are described to ensure the quality of the research.

3.1.1 Process design

The research process is divided into five phases. These are (1) structure, (2) theory, (3) practice, (4) review and (5) conclusion. An overview of the research steps within each phase can be found in Figure 3-1. The steps are represented as a linear sequence of activities. In reality however, the process will have a more iterative character.

FIGURE 3-1: OVERVIEW RESEARCH PROCESS
3.1.2 Research quality

Yin (2009, pp. 33-39) defines four tests to establish the quality of the research. These tests ensure to (1) construct validity, (2) internal validity, (3) external validity and (4) reliability of the research.

In order to construct validity, triangulation of sources will be used in two ways. The first way is to gather data from literature, documentation, people involved in the subject and the observation of the author. The second way is to send a questionnaire and organize interviews with experts involved in the cases to have multiple sources of evidence about influences and events during the lifespan of each case. For each case experts from at least three different disciplines will be interviewed. The proposed disciplines are operations, management and engineering.

Internal validity is created, in the first place, by a logic model (Yin, 2009, p. 127), which is in this research a theoretical framework. Second, an identification of the pattern of findings across multiple cases is made. This will be used to find the nature of causal relations between the variables of the theoretical framework.

The result of this research will be a decision-making framework. In order to create external validity, replication logic will be used. In practice this results in that the framework is applied to an actual case and expert interviews are done to evaluate on whether it is possible to apply the framework to other cases.

In order to ensure a reliable research, protocols are designed for data collection and a database of results is made.

The next sections will focus more in depth on the contents of the research process. The methodologies for the questionnaire, multiple-case study and the synthesis of finding into the proposed decision-making framework will be explained. It will also be shown how the quality in the practical research is ensured.

3.2 A questionnaire to explore the influences on the SoS

The questionnaire is used to gather a (world) wide range of knowledge and is primary focused towards the driving factors from the context on system performance and decision-making. The results provide insights into the nature of external causes of failures for liquefied natural gas (LNG) plants, gas terminals and refineries, but also a prioritization of main considerations during a system’s lifespan. The questionnaire is used for a smaller extent to make an inventory of successful lifetime extension strategies and to get a general understanding of the quality of maintenance and inspections in practice. More detailed information on the questionnaire design can be found in Appendix A.

The structure of the questionnaire is experience-based; the more knowledge the respondent has about a subject, the more questions are answered. This means that questions only can be answered by a respondent if he or she does have expertise in that certain subject. Therefore, the response (N) differs per question.

The strategy to capture the experiences about external influences is to develop a range of key words to choose from. By means of a short brainstorm session the key words are made for each category provided by the theoretical framework developed in chapter 2. The category ‘environmental effects’ for example, consists of the key words ‘Air pollution’, ‘Earthquake’, ‘Rain’, ‘Soil quality’, ‘Volcano’, ‘Water’ and ‘Wind speed’. The respondents can choose for one of these key words, or fill in a key word they missed. The answers are subdivided into the categories to find the actual key drivers within the theoretical framework.
In order to capture the insights and opinions of the respondents through multiple choice questions a Likert-scale created by Likert (1932) is used for this research. A Likert-scale is usually a 5-point or 7-point (ordinal) scale in which the middle point is the neutral option. However, there is a tendency for participants to opt for the mid-point of a 5-point or 7-point scale. (Cohen, Manion, & Morrison, 2007, p. 327). When using a forced choice scale the neutral option is removed. This means that the respondent needs to give an opinion and has the option to agree or disagree to a certain level on a given statement. Only in case the respondent does not know the answer, he or she can choose for the option 'I don’t know'. Disadvantage of using these kinds of scales is that the respondent might want to add any other comments about the issue under investigation. It might be the case that there was something far more pressing about the issue than the rating scale included but which was condemned to silence for want of a category (Cohen et al., 2007). Therefore, short answer questions are used to underpin the scores provided by the forced choice questions. This is also done to verify the respondent really understood the question and to find a pattern between the answers provided.

3.3 An embedded multiple-case study to explain the occurrence of phenomena

When the focus of the research lies on the ‘how’ and ‘why’ of certain phenomena it is likely to use a multiple-case study (Yin, 2009, pp. 6-7). Since there are multiple units of analysis for this research (system performance, inspections, interventions and decision-making), an embedded multiple-case study is done to gather in-depth knowledge about these units of analysis. The concept of replication logic (Yin, 2009, p. 47) is used to find patterns between the cases.

Case selection
The case used for validation of the result is CASE 4. More detailed information on the cases can be found in Appendix X. Shell has a share of 25% in the CASE 4 plant, and is mainly responsible for providing the technical support. Three comparable case studies are used in the research. The findings from this multiple-case study will be used for the framework that will be applied to CASE 4. The cases are selected based on the following criteria:

- **Onshore constructions.** The plants are established on a fixed location and cannot be moved from one place to another. The constructions are selected based on similarities in material and degradation process.
- **Life extension completed.** The plant is constructed more than 20 years ago and already had a lifetime extension.
- **Economy of scale.** The cases are selected on the size of the plant and the number of trains.
- **Location.** There are geographical differences between the locations of the plants, considering different external influences, such as climate, economy and politics.

The resulting selection of cases is shown in Table 3-1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Years in operation</th>
<th># LEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>± 40</td>
<td>1</td>
</tr>
<tr>
<td>Case 2</td>
<td>± 40</td>
<td>2</td>
</tr>
<tr>
<td>Case 3</td>
<td>± 30</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3-1: Selection of cases to be used for this research
3.3.1 Perspectives on cases

In order to capture complete, relevant, clear and valid information from the cases, the principle of triangulation of sources is used (Verschuren et al., 2010, p. 179). Three different perspectives, which are engineering, project leader and operations, were formulated. More background on these perspectives can be found in Table 3-2.

<table>
<thead>
<tr>
<th>Perspective</th>
<th>Description</th>
<th>Examples of functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision maker</td>
<td>Project or program manager of LE of the asset, has a general view on the case.</td>
<td>LE project / program manager</td>
</tr>
<tr>
<td>Operations</td>
<td>Someone who has worked at the plant for at least one year. Is familiar with the plant and provides insights into the daily operations of the case.</td>
<td>Plant manager, Discipline engineer, Operator</td>
</tr>
<tr>
<td>Engineering</td>
<td>Provided technical support to (parts of) the plant during the lifespan or LE project. Has detailed insights into failure mechanisms and technical solutions.</td>
<td>Discipline engineer</td>
</tr>
</tbody>
</table>

For each case the interviewees are asked to provide background information on the findings from the questionnaire. For each unit of analysis the following questionnaire results were provided to the interviewees:

- External influences from the context affecting system performance as well as decision-making.
- Point of views on inspection and maintenance practices.
- Factors mentioned for success and failure of inspections and interventions.

These results are the units of analysis within this research. A schematic overview of the different perspectives on a case, including its units of analysis, is provided in Figure 3-2.

The interview outcomes together with the documentation about the case are used to explain the reason behind the functioning of each unit of analysis in practice. This is done with the use of the coding method (Saldaña, 2012). Key words derived from the interview minutes are translated into codes. These codes are placed into categories, which are the variables of the theoretical framework. By combining the categories and its codes, the relationship between the variables can be described. The technique of pattern matching (Yin, 2009, pp. 26-34) is used to define the conclusion of the multiple-case study.
3.4 Synthesis to develop the four stage framework

The results of the multiple-case study provide insights about which influences on system performance and decision-making processes are decisive for the performance of the SoS. However, it is not known how one should take these aspects into account. Therefore, the influences are translated into elements for decision-making, as introduced in Chapter 2. For each decision element a strategy to arrive at the next stage and a description of the new situation is provided. By identifying the actual state of each decision element the decision-making process can be improved. An overview of this process is shown in Figure 3-3.

The four stage framework is applied to the CASE 4 case, so that the method is validated through a real situation. An expert review is done to evaluate on the usefulness of the framework. The results of the process described in this chapter will be discussed in the next three chapters.
4. DATA ANALYSIS: THE INFLUENCES WITHIN THE THEORETICAL FRAMEWORK

The theoretical framework created in chapter 2 consists of the SoS and the influences from the context on the SoS. This chapter will focus on the remaining knowledge gaps of the theoretical framework. Insights from practice give answers to the following research questions:

B. What are the decisive influences from the context affecting system performance?
C. What are the decisive influences from the context affecting the decision-making process?
D. What are the drivers determining the success of inspections and interventions?

The answers to the sub questions above provide insights into the influences affecting the SoS’s lifespan. The decisive influences are assumed to occur during the next lifespan of the SoS. Including these influences in the decision-making process for a LE will provide the opportunity to avoid unnecessary maintenance during the next lifespan of the SoS.

As described in chapter 3, the information is gathered with the use of a questionnaire and multiple-case study. First, the background information on the respondents of the questionnaire and the interviewees for the multiple-case study is provided. Subsequently, the external influences and the effect of maintenance on system performance are explored. The nature of these influences will be explained by analyzing the pattern of findings among the cases, which eventually leads to the influences to be considered for LE. After that, the external influences and the effect of inspections on the decision-making process are explored the same way as done for system performance. The chapter will be concluded with the practical framework providing the answers to the research questions.

4.1 Background information on used data

This section provides the background information on the sources used as input for this research. First, the sample of the questionnaire is described. This provides information about the respondents and the geographic distribution of the case where the respondents provided their insights about. After that the interviewees and documentation used as input for the multiple-case study is discussed.
4.1.1 Description sample questionnaire

The sample of the questionnaire consists of civil engineers from Shell. This sample group is considered to be experienced since the majority (59%) has more than 10 years of work experience. Most of the knowledge comes from the Europe, Middle East and Africa (EMEA) region (57%) and to a smaller extent from the region East (33%) and the region Americas (10%). There were 77 respondents after the responses were filtered per completed topic. The sample is considered to be reliable, because of the sufficient amount of respondents and their experience. The details on the sample characteristics and responses can be found in appendix B.

55 out of 77 respondents provided information on 25 different cases worldwide. The other 22 respondents did not have knowledge about a specific case. The geographic distribution of these cases is shown in Figure 4-1.

4.1.2 Description interviewees multiple-case study

For each case selected for the multiple-case study it was preferred to have a project leader, engineering and operations perspective so that preferences on a multilevel are considered. However, only for CASE 2 it was possible to find interviewees with all different perspectives willing to cooperate in this research. There were two interviewees involved in multiple cases in which they had different roles. This meant that they could evaluate on the project from different perspectives. All interviewees had more than 10 years of work experience and are therefore considered as an expert. Information from documentation was used to support the evidence. An overview of the interviewees and used documentation can be found in Table 4-1.

TABLE 4-1: SOURCES AND PERSPECTIVES ON THE MULTIPLE-CASE STUDY

<table>
<thead>
<tr>
<th>#</th>
<th>Perspective</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engineering</td>
<td>Engineering support for the LE of CASE 1</td>
</tr>
<tr>
<td>2</td>
<td>Operations</td>
<td>Current plant manager of CASE 1</td>
</tr>
<tr>
<td>3</td>
<td>Engineering</td>
<td>Engineering support for LE of subsystems at CASE 2 and CASE 4</td>
</tr>
<tr>
<td>4</td>
<td>Engineering</td>
<td>Engineering support at CASE 3, CASE 4 and multiple other cases</td>
</tr>
<tr>
<td></td>
<td>Operations</td>
<td>Worked at CASE 2</td>
</tr>
<tr>
<td>5</td>
<td>Project Lead</td>
<td>Project Leader first LE at CASE 2</td>
</tr>
<tr>
<td></td>
<td>Engineering</td>
<td>Engineering support at CASE 3 and multiple other LNG plants</td>
</tr>
<tr>
<td>6</td>
<td>Operations</td>
<td>Worked at CASE 4</td>
</tr>
<tr>
<td>7</td>
<td>Operations</td>
<td>Current civil lead at CASE 2</td>
</tr>
<tr>
<td>8</td>
<td>Operations</td>
<td>Current civil lead at CASE 4</td>
</tr>
<tr>
<td>9</td>
<td>Project Lead</td>
<td>Project Leader second LE at CASE 2</td>
</tr>
<tr>
<td>D1</td>
<td>Project Lead</td>
<td>Document summarizing the most important finding from respondent 5</td>
</tr>
<tr>
<td>D2</td>
<td>Project Lead</td>
<td>Evaluation of the LE of CASE 3</td>
</tr>
</tbody>
</table>

FIGURE 4-1: GEOGRAPHIC DISTRIBUTION OF THE CASES. MOST OF THE CASES USED ARE SITUATED NEAR THE SEA IN EUROPE, AFRICA AND SOUTH ASIA.
The interviewees provided in-depth knowledge on the nature of influences from the context and evaluated on the inspections, maintenance and the LE project at the site they were involved. Section 4.2 and 4.3 will discuss the results of the questionnaire and the results from the multiple-case study. These findings are combined in the last section.

4.2 Influences affecting system performance

This section examines the decisive influences from the context on system performance, as well as the drivers that determine the effectiveness of the interventions improving system performance. Figure 4-2 shows the part of research covered by this section.

4.2.1 Exploration: Influences from the context

The external influences were subdivided over specific key words and used as choices within the questionnaire. Respondents of the questionnaire also had the possibility to fill in the key words they missed. These were placed into the existing categories and can be found in Figure 4-3. A total of 3.2% of the responses could not be categorized because it was unknown when the failure occurred, or it was unknown how often the external influence caused a failure. The factor 'lack of maintenance' was mentioned several times and is therefore included as one of the factors. A more extensive discussion on this aspect can be found in section 4.2.3.
Figure 4-3 shows that the main causes of failure are environment effects and design and construction errors. This indicates that failures occur due to inadequacies in design and construction, but also climate conditions such as rain, water, and the soil quality. The effects are mostly visible within the first five years of operation. During the first half of the lifespan the process-specific effects became increasingly important, but after that it seems like these influences do not affect system performance anymore. This phenomenon is difficult to explain with the use of the information provided and will be explored more in depth in section 4.2.2.

Accidents and deliberate damage play a role to a smaller extent. The external influence deliberate damage was only mentioned in Nigeria and Libya and is therefore assumed to be a local problem. However, this influence will be taken into account in the rest of the research, since the decision-making model is validated with CASE 4, located in Nigeria. After the initial design life of approximately 20 years is finished, the most important causes of failures are design and construction errors and environmental effects and, to a smaller extent, a lack of maintenance. The next section will focus on why these phenomena occur.

4.2.2 Explanation: External influences on the lifecycles of selected cases

This section elaborates on how and why the influences from the context affected the lifecycles of CASE 1, CASE 2, CASE 3, and CASE 4. Only the conclusions for each case are provided, more detailed information can be found in Appendix D. The focus lies the most important results of the questionnaire (design and construction errors and environmental effects), but the other influences were not excluded from the case interviews.

During the lifecycle of the CASE 1, external influences on system performance were related to design and construction errors and process specific effect. Causes for the decrease of performance were (1) certain weak spots not being considered and (2) some process effects on materials were not taken into account in the initial design.

The failures during the lifespan of the CASE 2 site were related to corrosion. This was caused by the initial quality of the system not being fit for the local atmospheric conditions, as result of limited investment in quality during the design and construction phase.

“One of the pipes for water cooling is build up to a few kilometers into the jungle. After one kilometer the pipe did not need to be coated anymore, because there were no atmospheric influences causing corrosion.”

Interviewee – Civil engineer
During the lifecycle of the CASE 3 site, main damages were, in the first place, related to corrosion. This is also caused by the initial quality of the system not being fit for the local atmospheric conditions. However, recent design and engineering practices are more focused towards the initial quality. The other damages were related to process effects on materials, leading to replacement of components before the actual design life was finished. During the lifecycle of the CASE 4 site main damages were related to external corrosion, corrosion inside the systems and process effects on materials. This is caused by the initial quality of the system not being fit for the local atmospheric and process conditions. The latter resulted in limited availability of the system.

4.2.3 Exploration: Effectiveness of interventions during the lifecycle

In order to gain insights on the effectiveness of interventions the respondents were asked to what extent, on a scale from 1 to 6, the current maintenance practices were improving system performance and got the possibility to underpin the scores they provided. More details on the results can be found in appendix D.

There were 11 respondents providing their insights into why the current maintenance practices were successful and 12 respondents gave their insights into why the current maintenance practices failed. Figure 4-4 shows the summary and transition of responses into drivers for success and failure in the application of maintenance.

It can be concluded that the procedures enable an improvement of system performance. One respondent mentioned that the description of these procedures could be more unambiguous so that all practitioners know how to use them. The response for ‘early identification’ is merged with procedures, because it can be argued that early identification of failures is part of the procedures. Main drivers for the failure of these concepts are a lack of resources and wrong priorities at the site. The latter can be related to the organizational change, because it is hard to set the right priorities when there is a continuous in- an outflow of people involved in the maintenance plans. An opportunity for improvement mentioned was the use of new technologies. Two respondents explained that this could increase the efficiency and quality of maintenance.

4.2.4 Explanation: Effectiveness of interventions during the lifecycles of selected cases

This section elaborates on how and why interventions during the lifecycles of the CASE 1, CASE 2, CASE 3 and CASE 4 were effective. Only the conclusions for each case are provided, more detailed information can be found in Appendix D. The focus will lie on the most important results of the questionnaire, but the other success drivers mentioned in the questionnaire results were excluded from the case interviews. It can be concluded from CASE 1 that a lack of upgrades and maintenance resulted in a large investment for LE. The online execution of the LE meant that the work is done less efficient
and additional interventions are needed. To reduce cost and safety exposure off-site work was maximized.
During the lifespan of CASE 2 triggers to perform inspections and maintenance tasks together with adequate skills and knowledge were necessary to ensure sufficient maintenance effectiveness. Low organizational capacity and the knowledge that the recent upgrade provided a more reliable system were limiting the possibility to follow the advised inspection interval. Unique and innovative solutions provided possibilities to actually improve the initial quality of the system for the long term.

“The application of an offshore coating system seems a bit exaggerated, but it will last for a very long time.”

Interviewee – former project lead

At CASE 3 interference among different disciplines and insufficient knowledge and skills lead to an ineffective execution of the work.
At CASE 4 it was hard for the local organization to maintain the plant during its lifecycle due to a lack of knowledge about the plant, a lack of space and a lack of maintenance skills. It can be concluded from this case that proper spare part management is highly important to execute the maintenance tasks.

4.2.5 Decisive influences on system performance
Starting point for assessing the nature of influences on system performance is the initial quality of the design. Based on the findings of the multiple-case study as seen in 4.2.2 and 4.2.4 it can be concluded that three types of ‘design and construction errors’ are limiting the initial quality of the system. These are:
- The initial design is not being fit for purpose for local climate conditions,
- The underestimation of process effects on materials,
- A focus on low project costs.

The first error is that the initial design is not fit for purpose for local climate conditions, because the materials used were not fit for purpose. This was the case at CASE 2, CASE 3 and CASE 4. One could argue that these sites have similar (tropical) climate conditions and that this kind of error is an exceptional case. However, interviewee_5 has experienced that the climate conditions at other LNG sites, such as Australia, have similar effects despite the fact that these local climate conditions are less tropical. These kinds of errors are typically a problem near the coast, explains interviewee_2.

The second error can be concluded from CASE 4 and CASE 1. The process effects on materials were underestimated, or insufficiently taken into account. This kind of error is related to the weak spots, or attention to detail, which was insufficient in design and construction processes. Interviewee_4 explains that this is due to the inconvenient planning of the execute phase, meaning that the time pressure of this phase affects the quality of the design. Especially for blast cleaning and painting the system, the completion is insufficient. The last error, related to the time pressure, was that the focus during the design and execute phase was on lowering the project costs. In addition, interviewee_1 explains that the initial quality of the system is dependent on the ability of the contractor to deliver a sufficient level of quality. In practice, this level of quality is established with the use of a specification of work.
Effective interventions are characterized by the focus on quality, or the improvement of the initial quality of the system. Adequate knowledge and skills are key drivers to assess the actual state of the system and to execute maintenance tasks the right way. Innovative and unique solutions provide the opportunity to actually improve system performance. These kinds of solutions are not necessarily high-tech solutions; the off-site construction of components at CASE 1 or the application of an offshore coating system at the LNG plants shows that a certain level of creativity improved the interventions. Triggers and proper spare part management are needed to ensure that the actual maintenance tasks are executed.

Interventions were ineffective due to postponing, or even lacking execution of (preventive) maintenance tasks, resulting in reactive maintenance. This was in some cases related to a lack of knowledge and skills or to a small capacity of the organization. As shown in CASE 3, interference among different disciplines can lead to inefficient execution of the work. Above described influences are summarized in Figure 4-5.

The decisive influences on system performance are explored and explained. The next section focuses on the influences on the decision-making processes.
4.3 Influences affecting decision-making

This section examines the influences from the context on the decision-making process, as well as the drivers determining the quality of inspections. Figure 4-6 provides an overview of the part of research covered by this section.

![Diagram showing influences affecting decision-making]

4.3.1 Exploration: External influences on decision-making processes

The influences from the context affect the decisions made during the lifespan of the system. In this section an analysis is made of the contribution of these influences from the context during the lifespan of the selected cases. After that, the importance of the influences and the awareness of the people involved about these influences are discussed. For this topic the questionnaire provided 156 responses (N=38). These were less respondents than the respondents for system performance, because some of the respondents were not able to provide their insights.

Most of the responses were related to costs, management skills, norms and regulations and, for a smaller extent, to demand, supply and knowledge (see Appendix B). These aspects are considered as the key drivers from the context.

In order to find out whether these aspects should be included in the final framework, the respondents were asked to what extent these aspects are important and whether or not they were aware of these influences before these occurred. The respondents were forced to choose for an option from 1 to 6, or the option ‘I don’t know’. The options 1 to 3 meant that the influence was not important and the options 4 to 6 meant that influence was important. The initial awareness was indicated by the options ‘Yes’, ‘No’ or ‘I don’t know’. The number of times the option ‘Yes’ or ‘No’ was chosen is translated into factors ranging from -3 to 3. Figure 4-7 shows the importance and the initial awareness of external influences. Influences from the context are considered as a negative influence when the awareness of this influence is low and the importance is high. For highly important influences it is preferred that the awareness of the actual influence is also high. This means that influences categorized as ‘low awareness and high importance’ are considered for this research.
The decisive external influences are norms and regulations, demand and supply, knowledge and management related aspects. These influences are highly important, but one is unaware of these influences before these occur. Therefore, these influences will be considered in decision-making processes and will be explored more in depth.

The external influence ‘costs’ is important, but in general the respondents were more aware of influences related to this influence and took action before the influence had a negative impact on the decision-making process.

4.3.2 Explanation: External influences on decision-making processes of selected cases

This section elaborates on how and why the decisive influences from the context affected decision-making processes of the CASE 1, CASE 2, CASE 3 and CASE 4. Only the conclusions for each case are provided, more detailed information can be found in Appendix D. The focus lies on the most important results of the questionnaire (management, knowledge, norms and standards and demand and supply), but the other influences were excluded from the case interviews.

At CASE 1, obsolescence of equipment and the adoption of new norms and standards led to a large part of the investment for LE, because the plant was not continuously upgraded during the lifespan. Lower production quantities inherently meant that the operational expenditures (OPEX) needed to be decreased. Therefore, the LE is used to downscale the plant. There is a lack of civil knowledge present at the site, resulting in a lack of attention to civil structural aspects and wrong priorities. It was highlighted by the interviewees that the use of a wrong approach leads to a worse state of the plant.

Also at the CASE 2 site new norms and standards were reasons for replacement of components. Priorities were not always set the right way, due to an underestimation of civil
engineering and a continuous change of management. The latter happened because it was hard to find the right person for the job, due to the policy to embed local workforce in all levels of the local organization. Also budgets are under spent, because lifecycle costs are not considered.

“In LNG business there is a sufficient amount of money available, but it is hard to spend it the right way.”

Interviewee – Civil engineer

There was less information about decision-making processes at CASE 3 provided. However, there were some issues with the contractor used for the LE. From this case it can be concluded that the selection of contractors is an important driver for the approach used for LE. A 'greenfield' approach led to a major scope and cost indication.

At CASE 4 the decision-making process is mainly dependent on the demand of the customers and economic considerations. There was a lack of knowledge at the CASE 4 site. This was resolved by bringing expats with the required knowledge to the site.

4.3.3 Exploration: Quality of inspections during the lifecycle

Evaluating the former inspections provides information about to what extent inspections in general provide a sufficient amount of information to make decisions.

The respondents were asked to what extent, on a scale from 1 to 6, the inspections provided sufficient information for decision-making. The respondents also got the possibility to underpin the scores they provided.

In general, one is slightly positive about the supply of information, but this does not tell anything about what aspects determine a sufficient supply of information. Therefore, the underpinnings on the scores are categorized in successful aspects and aspects for improvement, which can be found Figure 4-8.

There were a lot of responses for improvements. One of the respondents stated that the organization should be much more in control. This can be linked to the priorities and effort needed to actually execute the inspections. A reduction of available workforce for inspection made it even more difficult.

The other drivers for failure and success are related to skills and knowledge. The (external) inspector needs to have a sufficient amount of knowledge of the plant, before he or she can actually assess the current state of the plant. This way it might be easier to focus on what the actual scope of work is. Concluding, in general the amount of data is sufficient, but there is room for improvement in the amount of workforce, knowledge and skills, effort and the focus and priorities for the tasks that should be done.
4.3.4 Explanation: Quality of inspections during the lifecycles of selected cases

This section elaborates on how and why the quality of data gained from inspections affected the decision-making processes of the CASE 1, CASE 2, CASE 3 and CASE 4. Only the conclusions for each case are provided, more detailed information can be found in Appendix D. The focus will lie on the most important results of the questionnaire (local organization, skills and knowledge), but the other success drivers mentioned in the questionnaire results were excluded from the case interviews.

Regarding to the quality of inspections at the CASE 1 site, insufficient inspection effort at led to an impossible scope of work for LE. This is related to unclear responsibilities for civil maintenance.

CASE 2 showed that sufficient skills are needed for inspections and also for the reporting of findings. The inspection interval is lower than advised due to limited team size and the recent LE.

From CASE 3 it can be concluded that insufficient inspection effort resulted in a LE scope larger than necessary. The lessons learned from this case are applied in new cases.

A lack of knowledge and skills caused also issues at CASE 4. In the beginning of the lifespan people at the site were not able to perform an inspection properly due to a lack of skills and knowledge. For the coming LE inspections are done and the results, including recommendations for action, are stored in documentations.

4.3.5 Decisive influences on decision-making

In two of the cases the economic value of the plant directly affected the considerations made during the lifespan of the plant. For the CASE 1 site this meant that the LE was used to downscale the plant in order to decrease the OPEX. Interviewee_1 explains that one must understand that during a LE the design life of the plant is extended, but that this decision is only made when the initial design life is finished. There is still a sufficient amount of gas in the field near the plant. Therefore, one should understand why the LE is done.

The adoption of new norms were the reason to replace some components at two of the sites, resulting in an additional scope and investment. Interviewee_1 explains that the decision to upgrade the plant in order to comply with the new norms is dependent on the economic value of the site. In case this economic value decreases, it is not worth the investment. However, interviewee_4 highlights to be careful with the adoption of new norms and standards. These norms and standards need to be used to establish the level of safety for the next contract period. It is important that the important norm changes are not overlooked, such as for example, new norms for earth quakes. Summarizing, on the one hand the adoption of new norms and standards provides the possibilities to improve the system’s performance, but on the other hand it can lead to a large scope and more investments.

As result of technological changes over time, the phenomenon of obsolescence can occur. Some systems cannot be maintained anymore and need to be replaced with a new system. This was the case at CASE 1 for electrical and rotating equipment. Interviewee_5 explains that modern (LNG) plants are often obsolete because of IT-systems, which have an average lifetime of 10 years. Also rotating equipment has a useful life of 10 years.

In all of the cases there was a lack of knowledge present at the sites. Main reasons were:

- A continuous change of management,
- The policy to embed local workforce made it hard to find the right person for the job,
- The lack of contractor experience in brownfield projects, leading to a major scope and cost indication.

Previous describes causes affected the quality data gained by of inspections, but also the decisions made and the effectiveness of interventions. For the decision-making process in
particular, civil engineering was underestimated in two of the cases. This led to a lack of attention to civil structural aspects and the wrong priorities. However, interviewee_1 and interviewee_4 explain that civil and safety aspects are often the cost drivers. The civil scope mainly includes thermal insulation, meaning that the size of the plant is the cost driver.

The quality of inspections is determined by the effort of the inspector and the team size, as shown in CASE 2. A lack of knowledge and skills is also related to reporting the finding. The influences affecting the decision-making process are summarized in Figure 4-9.

![Figure 4-9: Overview of the nature of influences on decision-making processes.](image)

### 4.4 Sub conclusions

This chapter’s goal was to gain insights into the influences affecting the SoS’s lifespan, so that these influences can be included in the decision-making process for a LE. The research questions provided in the beginning of this chapter are answered by evaluating the nature of the decisive influences on the SoS and the success drivers behind inspections and interventions. The theoretical framework will be transformed into a practical framework.

What are the decisive influences from the context affecting system performance?

The starting point for assessing the nature of influences on system performance is the initial quality of the design. It can be concluded that four kinds of ‘design and construction errors’ are limiting the initial quality of the system. These errors are:

1. **Initial design** - The first error is the initial design not being fit for purpose for local climate conditions, because of the use of wrong materials. This type of error occurs at sites near the coast and along the shore. Main reason for failure during the plant’s lifespan is related to the saline environment rather than tropical conditions.
2. **Process effects on materials** - The second error is the underestimation of process effects on materials due to weak spots and insufficient attention to details. One of the reasons for this is the pressure on the planning during the execute phase.

3. **Focus on low project costs** - Related to the time pressure, the third error is the focus on low costs during the design and execute phase. The focus was on short term benefits instead of long term benefits. However, there seems to be a tendency to focus more and more on long term benefits.

4. **Inability of contractor to deliver the quality** - The fourth error is the inability of the contractor to deliver the quality. The initial quality of the system is dependent on a specification in which this quality level is established.

What are the decisive influences from the context affecting the decision-making process?

There are four external influences on decision-making processes. These are:

1. **Demand and supply of gas** - The first category of external influences to be considered is the demand and supply of gas. A change compared to the initial prognosis for the amount of gas is the driver for a LE. In case an LE is needed, but the second economic life is shorter than the first economic life, the LE can be used to downscale the plant through the concept of de-complexing.

2. **New norms and standards** - The second category of external influences is new norms and standards. On the one hand the adoption of new norms and standards provides the possibilities to improve the performance of the system, but on the other hand it can lead to a large scope and investment. The decision to upgrade the plant in order to comply with the new norms is dependent on the economic value of the site. In case of a decrease of economic value, it is not worth the investment.

3. **Knowledge and skills** - The third category is the amount of knowledge and skills. In all of the cases there were periods during the lifespan that there was a lack of knowledge at the sites. Main reasons were a continuous change of management, the policy to embed local workforce and the limited experience of the contractors. The latter is related to a ‘greenfield’ approach, which led to a major scope. A lack of knowledge and skills leads to a lack of attention to civil structural aspects and the wrong priorities.

4. **Technological change** - The last category is technological change and related to obsolescence of components. Some parts of the plant have a shorter design life than other parts. Over time there are often new technologies developed. This results in replacement of sub systems by new types of systems.

What are the drivers determining the success of inspections and interventions?

Successful inspections and interventions are characterized by the following drivers:

1. **Focus on initial quality** - The first characteristic, the focus on the initial quality of the system, involves the identification of the external influences on system performance, as discussed in section 4.2.5. This way the gaps between the initial quality of the system and its operating context can be resolved.

2. **Unique and innovative solutions** - The second characteristic, unique and innovative solutions, provides the opportunity to actually improve system performance. These kinds of solutions are not necessarily high-tech solutions; the off-site construction of components at the CASE 1 site, or the application of an offshore coating system shows that a certain level of creativity improved the interventions.

3. **Triggers** - The third characteristic, triggers, is needed to avoid postponing, lacking execution or insufficient effort to execute tasks. Multiple cases showed that these aspects resulted in reactive maintenance tasks and a large scope for LE.
4. **Resource management** - The fourth characteristic, proper resource management, includes ensuring that there is a sufficient amount of spare parts, tools and equipment are present so that the intervention can actually take place. This is related to the new technologies as discussed in section 4.3.5.

However, there were also drivers for failure in found in the evaluation of inspections and interventions. There were:

1. **Postponing or lacking execution of work** - Postponing, or even lacking execution of (preventive) maintenance tasks, resulted in reactive maintenance. In this case there are insufficient priorities for the application of maintenance.
2. **Lack of knowledge and skills** – Previous driver, postponing or lacking the execution of work, was in some cases related to a lack of knowledge and skills or to a small capacity of the organization.
3. **Interference** – Interference among different disciplines, or lack of space, leads to inefficient execution of the work. It seems like the disciplines are focused on their own work and that there is a lack of understanding of the broader view on the LE.

It can be concluded that in order to ensure successful interventions, a sufficient amount of workforce with adequate knowledge and skills are needed to identify the gap between the initial quality of the system and its operating context.

**Resulting practice-based SoS**

The answers to the sub questions provided in this chapter enables the theory-based SoS to be transformed into a ‘real life’ practice-based SoS. In the practice-based SoS, shown in Figure 4-10, the decisive influences, as well as the success drivers for interventions and inspections, are identified.

![Figure 4-10: Practice-Based SOS as Result of This Chapter](image-url)
5. RESULTS: DEFINING THE LIFETIME EXTENSION STRATEGIES

In this chapter the preferences from an operations, engineering and project management perspective are used to embed the decisive external influences and success drivers into the decision-making process. The following research questions will be answered:

E. How can the success drivers and decisive influences be embedded into the decision-making process to maintain the system’s performance?

F. What are the possible strategies for a lifetime extension?

Figure 5-1 provides an overview of the part of the research explored in this section. First, the decision elements for the asset organization and the LE are identified. After that, the strategies for LE are defined to complete the four stage framework for LEs.
5.1 Decision elements for LEs

In this section the decision elements needed as an input for the SoS are defined. The perspectives project lead, operations and engineering are used to identify the preferred decision elements for the asset organization and the LE. These are compared and validated with the decision elements provided in chapter 2. This results in the final decision elements needed for the asset organization and the LE.

5.1.1 Preferred decision elements

As concluded in Chapter 2, the preferences from practice are needed to establish the decision elements. The maintenance decision elements defined by Pinjala et al. (2006) are transformed into decision elements for LEs through expert recommendations. The interviewees were asked ‘Which decision should be made for the LE?’ and ‘What are your further recommendations regarding LEs?’ Appendix C provides the raw data of answers provided. Some interviewees mentioned certain decision elements more than once. Therefore, each decision element was only counted once per interviewee. The answers are summarized and categorized in Figure 5-2.

None of the project leaders mentioned the decision element ‘knowledge and skills’. This can be explained by the possibility that the project leader has more insight into the reason behind the phenomenon and is focused on the source of this problem. Besides, it was concluded in chapter 4 that the contractor, inspector and local workforce influence the knowledge about the system and the skills needed. Therefore, it can be argued that the decision elements ‘contracting’, ‘inspection strategy’ and ‘local workforce’ include the effects of the influence ‘knowledge and skills’. The decision element ‘resources’ was not mentioned by interviewees with the operations perspective, but obsolescence was acknowledged as an issue by multiple interviewees in chapter 4. The other decision elements were acknowledged by all perspectives. Taking these into account ensures that the preferences of multiple perspectives are included.

5.1.2 Establishment of decision elements

The decision elements can be distinguished on whether these are related to the asset organization or specifically to the LE. As explained in Chapter 2, decision elements related to the asset organization can be seen as ‘fixed’ elements and difficult to be changed, while the decision elements related to LEs are ‘flexible’ elements.

Table 5-1 provides an overview of the decision elements related to the asset organization and the decision elements related to LEs. The decision elements are compared and validated with the decision elements established by Pinjala et al. (2006) in chapter 2.
TABLE 5-1: DECISION ELEMENTS FOR LIFETIME EXTENSIONS

<table>
<thead>
<tr>
<th>Pinjala et al. (2006)</th>
<th>Multiple-case study</th>
<th>LE Decision element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural decision elements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance capacity</td>
<td>Workforce local organization</td>
<td>Asset organization</td>
<td>Amount of knowledgeable and skilled workforce present</td>
</tr>
<tr>
<td>Maintenance facilities</td>
<td>Local resources</td>
<td>Workforce</td>
<td>Amount of spares, tools, equipment present</td>
</tr>
<tr>
<td>Maintenance technology</td>
<td>-</td>
<td>Facilities</td>
<td>Maintenance management technology and performance measurement technology present</td>
</tr>
<tr>
<td>Vertical integration</td>
<td>-</td>
<td>Available technology</td>
<td>Current outsourcing contracts, ratio in-house versus outsourcing</td>
</tr>
<tr>
<td>Infrastructural decision elements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance organization</td>
<td>Contracting strategy, Team composition</td>
<td>Contracting</td>
<td>The contracting strategy needed for the LE, based on the actual workforce and vertical integration</td>
</tr>
<tr>
<td>Maintenance policy and concepts</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
<td>Scope definition for the LE, based on the current knowledge about the system’s performance and facilities present, aligned with the planning and costs for LE and daily maintenance and operations</td>
</tr>
<tr>
<td>Maintenance planning and control systems</td>
<td>Planning and costs</td>
<td>Planning and costs</td>
<td>Available budget for the LE, aligned with the scope and daily maintenance and operations and facilities present</td>
</tr>
<tr>
<td>Human resources</td>
<td>Contracting strategy, Team composition</td>
<td>Team composition</td>
<td>Team members included for the LE, based on the actual knowledge about the system’s performance and contracting strategy</td>
</tr>
<tr>
<td>Maintenance modifications</td>
<td>LE versus daily maintenance</td>
<td>Daily maintenance and operations</td>
<td>Division of work packages for the LE and daily operations, based on facilities present and the scope and budget for the LE</td>
</tr>
<tr>
<td>Maintenance performance measurement and reward system</td>
<td>Inspections strategy</td>
<td>Performance measurement and reward system</td>
<td>Performance measurement system as result of the LE, based on available technology and the scope of the LE</td>
</tr>
</tbody>
</table>

Most of the decision elements from the multiple-case study correspond with the decision elements adapted from Pinjala et al. (2006). The following considerations are made to establish the decision elements for LEs:

- The structural decision elements correspond with decision elements for the asset organization in case of an LE. The infrastructural decision elements include maintenance management decision elements and correspond with the decision elements for the LE. The LE strategy is the result of the combined decision elements for LE, depending on the maturity of the asset organization.

- The decision element ‘maintenance facilities’ is defined as ‘Tools, equipment, spares, workforce specialization (mechanics, electricians, etc.), location of workforce’ (Pinjala et al., 2006). It can be argued that local resources are a part of an asset organization's facilities. ‘Workforce’ is already considered as a separate decision element. therefore, ‘facilities’ include the spares, tools and equipment present in the asset organization.

- ‘Maintenance technology’ was defined as ‘Predictive maintenance, or condition monitoring technology, expert systems, e/I maintenance technology (intelligent maintenance)’ (Pinjala et al., 2006). In the multiple-case study there were no responses for decision elements covering these aspects. Therefore available technology is in this research defined as the Maintenance management technology and performance measurement technology present in the asset organization.

- ‘Vertical integration’ was defined as ‘In-house maintenance versus outsourcing and relationship with suppliers’ (Pinjala et al., 2006). For LEs the decision elements ‘contracting’ was already included. However, existing contracts of the asset organization need to be considered for the LE strategy. In this research ‘Vertical integration’ is defined as the current outsourcing contracts and the ratio in-house workforce versus outsourcing.

- As explained in section 5.1.1, the decision element ‘knowledge and skills’ is covered by the local workforce, contracting strategy, inspection strategy and team composition and will therefore not be included as a separate decision element.
The decision elements need to respond to the influences from the context and consider success drivers, so that the SoS is fit for LEs. In the next section the decision elements for the asset organization are structured to respond to the influences on the SoS.

5.2 Four stages of the asset organization

In this section the four maturity stages of the asset organization are developed. Figure 5-3 provides an overview of which decision elements for the asset organization includes decisions to respond to the external influence.

More than one decision element enables a mitigation of the effects of each influence on the SoS. The decision elements are used in such way that four stable maturity stages of the SoS are created. For the asset organization the decision elements ‘Workforce’, ‘Facilities’, ‘Available technology’ and ‘Vertical integration’ are discussed in section 0 to 5.2.4. The interviewees provided their recommendations regarding the decision elements. However, these were not related to a certain stage. Therefore, the analyses are based on the recommendations combined with the relationships shown in of Figure 5-3. The raw data of recommendations provided by the interviewees can be found in Appendix E. The resulting four stage framework for LEs will be discussed in section 5.4.
5.2.1 Workforce

In this section, the four stages of the decision element ‘workforce’ are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to analyze the contents of each situation.

Definition of the strategies for each stage

Stage 1: No strategy - Uncontrolled management of workforce, resulting in a lack of quality of inspections, over maintaining or a lack of maintenance of the system.

Stage 2: Implementation strategy – Mitigate the effects of the influences ‘lack of knowledge and skills’, ‘effort’ and ‘insufficient capacity’

Stage 3: Supporting strategy – Create internal support by connecting with the decision element ‘vertical integration’.

Stage 4: Driving strategy - Ensure continuity and competitive advantage using the influences ‘knowledge and skills’ and ‘capacity’.

Case based evidence for the contents of the four stages

Stage 1: Postponing or lacking of execution of tasks resulting in corrective measures. CASE 2 showed that due to the policy to embed local workforce in all levels of the local organization, it is hard to find the right person for the job resulting in the lack of execution of tasks.

Stage 2: Add workforce (local management and inspectors) with sufficient operational skills and knowledge, by acquiring (temporary or fixed) workforce and training the existing the workforce, as recommended by interviewees 2, 6 and 7. Chapter 4 showed that a sufficient amount of skilled and knowledgeable workforce is needed to ensure successful interventions.

Stage 3: Interviewee_4 recommends to perform a skill test to measure the knowledge and skills present in the organization. By defining which tasks are done by in-house workforce and which tasks are done by contractors the skills and knowledge needed for the system and amount of workforce with tasks to be executed can be aligned.

Stage 4: The knowledge gained on system performance can be shared with other organizations (within the business), as strongly recommended by interviewee_4 and supported by the interviewees 2, 5 and 6. Continue to improve the alignment of workforce with the right skills and knowledge.

Table 5-2 summarizes the contents of each stage. This will be part of the final four stage framework.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement: Add (temporary) workforce with sufficient operational skills and knowledge. Train existing workforce.</td>
<td>Support: Align workforce with tasks to be executed. Perform skill tests.</td>
<td>Knowledge and skills needed are aligned with the system’s performance</td>
<td>Drive: Use workforce to support other asset organizations.</td>
</tr>
<tr>
<td>Insufficient amount of skilled and knowledgeable workforce resulting in postponing or lacking execution of tasks.</td>
<td>The workforce at the organization is able to preventively respond to failures</td>
<td></td>
<td>Continuity of workforce at the organization. Workforce shares knowledge and skills with other organizations (within the business).</td>
</tr>
</tbody>
</table>
5.2.2 Facilities

In this section, the four stages of the decision element ‘facilities’ are discussed. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to analyze the contents of each situation.

Definition of the strategies for each stage
Stage 1: No strategy - Uncontrolled management of facilities, resulting in obsolescence of parts and corrective responses to new norms and regulations or changed demands.
Stage 2: Implementation strategy – Mitigate the effects of the influences ‘norms and regulations’ and ‘demand and supply’, prevent ‘obsolescence’.
Stage 3: Supporting strategy – Create internal support. There is no direct connection with other decision elements.
Stage 4: Driving strategy - Ensure continuity and competitive advantage using the influences obsolescence’, ‘norms and regulations’ and ‘demand and supply’.

Case based evidence for the contents of the four stages
Stage 1: As concluded in chapter 4, an insufficient amount of spares, tools, equipment can lead to early replacement of components in the case of new technological developments entering the market. Some components were not available anymore and needed to be replaced for a new type of component.
Stage 2: Implement a facility management system, including spares, tools and equipment, to mitigate the effects of the influences ‘obsolescence’, ‘norms and regulations’ and ‘demand and supply’. Interviewee_1 & 4 state that the facilities present need to be considered before taking action. Therefore, the system needs to store the current and future needs of facilities. This also includes the identification of new technological developments.
Stage 3: Negotiate with the vendor about the facilities to align the organization’s needs with newly developed systems and components, as recommended by interviewee_5. This way the facility management system is aligned with the market.
Stage 4: Use the knowledge gained about the influences obsolescence’, ‘norms and regulations’ and ‘demand and supply’ by ensuring an industry wide involvement in the development of new technologies. This enables the organization to benefit from new technological developments.

Table 5-3 summarizes the contents of each stage and will be part of the final four stage framework.

<table>
<thead>
<tr>
<th>TABLE 5-3: FOUR STAGES OF FACILITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1</strong></td>
</tr>
<tr>
<td>Uncontrolled management of facilities, resulting in obsolescence of parts and corrective responses to new norms and regulations or changed demands.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
5.2.3 Available technologies

In this section, the four stages of the decision element ‘available technology’ are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to analyze the contents of each situation.

Definition of the strategies for each stage
Stage 1: No strategy - No or basic technologies, resulting in a low quality of inspections, over maintaining or a lack of maintenance applied to the system.
Stage 2: Implementation strategy – Mitigate the effects of the influences 'knowledge and skills', 'effort', 'process effects on materials' and 'local climate conditions', include 'triggers'
Stage 3: Supporting strategy – Create internal support by connecting with the decision element 'vertical integration' and 'workforce'.
Stage 4: Driving strategy - Ensure continuity and competitive advantage using the influences, 'process effects on materials' and 'local climate conditions'.

Case based evidence for the contents of the four stages
Stage 1: Interviewee_6 explains that the first step is a visual inspection. In the first stage, there are limited technologies for inspections or maintenance. The limited inspection technology results in corrective measures.
Stage 2: Implement a performance measurement system to document ‘process effects on materials’ and ‘local climate conditions’. Interviewee_4 and 7 recommend to include triggers or incentives to execute tasks and to track new developments on condition monitoring technology to increase the intervention's effectiveness. The knowledge derived from the performance measurement system enables preventive measures.
Stage 3: Connect with ‘workforce’ and ‘vertical integration’ by ensuring that the workforce and contractors use the performance measurement system. Use skills and knowledge present in the organization to improve the performance measurement system. Sufficient data about the system’s performance is available and used as trigger to intervene when needed.
Stage 4: Create (an industry wide) involvement in the development of new performance measurement technologies. Knowledge gained on the influences ‘process effects on materials’ and ‘local climate conditions’ is shared with other organizations (within the business).

Table 5-4 summarizes the contents of each stage. This will be part of the final four stage framework.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited availability of technologies for inspections and maintenance, resulting in corrective measures.</td>
<td>Implement: Performance measurement system to document external influences on system performance. Include triggers for execution.</td>
<td>Support: Ensure that the workforce and contractors use the performance measurement system. Use workforce to improve the performance measurement system.</td>
<td>Drive: Create involvement in the development of new performance measurement technologies. Share knowledge with other asset organizations.</td>
</tr>
<tr>
<td>The knowledge generated by the performance measurement system enables preventive measures.</td>
<td>Sufficient data about the system's performance is available and used as trigger to intervene when needed.</td>
<td>Other asset organizations benefit from knowledge gained about the performance measurement system.</td>
<td></td>
</tr>
</tbody>
</table>
5.2.4 Vertical integration

In this section, the four stages of the decision element ‘vertical integration’ are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to analyze the contents of each situation.

Definition of the strategies for each stage

Stage 1: No strategy - No outsource management strategy, resulting on the one hand in the inability of contractor to deliver the quality and, on the other hand, a lack of knowledge and skills needed to maintain the system’s performance.

Stage 2: Implementation strategy – Mitigate the effects of the influences ‘lack of knowledge and skills’ and ‘initial quality of the system’, include the driver ‘specification of work’.

Stage 3: Supporting strategy – Create internal support by connecting with the decision element ‘workforce’.

Stage 4: Driving strategy - Ensure continuity and competitive advantage using the influences ‘knowledge and skills’ and ‘initial quality of the system’, include the driver ‘specification of work’.

Case based evidence for the contents of the four stages

Stage 1: No outsource management strategy, resulting in a lower quality of work needed and a lack of knowledge and skills to maintain or restore the system's performance.

Stage 2: Interviewee 4 & 5 recommend to use contractors specialized in maintenance. In order to focus on the initial quality of the system, interviewee 1 & 8 recommend to make a clear specification of work.

Stage 3: Connect with the decision element ‘workforce’ by ensuring tighten supervision of contractors, as recommended by interviewee 4 & 8. It is Shell’s policy to use engineering and procurement contracts (EPC), which does not include maintenance and operational aspects. Interviewee 4 recommends to use innovative contracts. By defining which tasks are done by in-house workforce and which tasks are done by contractors, the amount of skilled and knowledgeable workforce is aligned with the tasks to be executed.

Stage 4: Share lessons learned on work packaging with other asset organizations. Continue to maintain the knowledge and skills in the in-house and outsourced workforce.

Table 5-5 summarizes the contents of each stage. This will be part of the final four stage framework.

<table>
<thead>
<tr>
<th>Table 5-5: Four Stages of Vertical Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1</strong></td>
</tr>
<tr>
<td>Implement: Use contractors specialized in maintenance. Make clear specification of work.</td>
</tr>
<tr>
<td>The contractor is not able to deliver the quality needed to maintain or restore the system’s performance.</td>
</tr>
<tr>
<td><strong>Stage 2</strong></td>
</tr>
<tr>
<td>Support: Ensure tighten supervision. Make clear definition of in-house versus outsourced tasks and reconsider contracts.</td>
</tr>
<tr>
<td>The contractor’s focus is on restoring, maintaining (or even improving) the initial quality of the system.</td>
</tr>
<tr>
<td><strong>Stage 3</strong></td>
</tr>
<tr>
<td>Drive: Share lessons learned on work packaging with other asset organization. Continue to maintain the knowledge and skills in the in-house and outsourced workforce.</td>
</tr>
<tr>
<td>The amount of skilled and knowledgeable workforce is aligned with the tasks to be executed.</td>
</tr>
<tr>
<td><strong>Stage 4</strong></td>
</tr>
<tr>
<td>Other asset organizations benefit from knowledge gained on work packaging and vertical integration.</td>
</tr>
</tbody>
</table>
5.3 Four stages of decision elements for the lifetime extension

In this section the LE strategies per maturity stage of the asset organization are developed. The decision elements for LEs do not only include success drivers and responses to the decisive influences, but also the current state of the related decision elements of the asset organization.

Section 5.2 showed four current states of the asset organization. An LE strategy can be defined, depending on these states. There are also multiple decision elements for the LE. The decision elements need to be used in such a way that four maturity stages of the SoS are created. The decision 'Contracting', 'Focus and priorities', 'Planning and costs', 'Team composition', 'Daily maintenance and operations', and 'Performance measurement and reward system' are discussed. Figure 5-4 shows the decision elements for the LE and their connection to the asset organization.

In the next sections, the four stages of the LE are defined. The analysis done is based on the recommendations derived from the case interviews, the stages of the asset organization discussed in section 5.2 and on logical reasoning. The raw data of recommendations provided by the interviewees can be found in Appendix E. The resulting four stage framework for LEs will be discussed in section 5.4.
5.3.1 Contracting

In this section, the four stages of the decision element ‘contracting’ are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used for the contents of each situation.

Definition of the strategies for each stage

Stage 1: No strategy – The contractor is unable to deliver the preferred quality.
Stage 2: Implementation strategy – Mitigate the effects of the current state of ‘workforce’ and ‘vertical integration’ of the asset organization, use driver ‘specification of work’
Stage 3: Supporting strategy – Create internal support by connecting with the decision element ‘team composition’.
Stage 4: Driving strategy - Ensure continuity and competitive advantage using the current state of ‘workforce’ and ‘vertical integration’ of the asset organization, use driver ‘specification of work’

Case based evidence for the contents of the four stages

Stage 1: Interviewee_1,4 and 5 explain that using a contractor inexperienced with LEs and maintenance leads to a lower quality of the construction, a major scope and potential cost overruns due to the use of wrong insights.
Stage 2: Make an inventory of the current knowledge and skills of present workforce in the organization and the existing contractors. Use a thorough specification of work (as means for agreements) for outsourcing, as recommended by interviewee_1 and 8. This will establish the quality level of the work is established.
Stage 3: In the asset organization a division is made of in-house and outsourced tasks, based on knowledge and skills. Use contractor already specialized in maintenance projects or daily experience in “what type of maintenance is needed”, as recommended by interviewees_1,4 and 5. Involve contractor in the LE team to ensure high quality and a realistic scope of work from all perspectives.
Stage 4: Current workforce and contractors are able to execute the LE. Share lessons learned on work packaging with other organizations. At this point, the contractor is one of the sources for new ideas and opportunities.

Table 5-6 summarizes the contents of each stage. This will be part of the final four stage framework.

| TABLE 5-6: FOUR STAGES OF CONTRACTING |
|---|---|---|---|
| **Stage 1** | **Stage 2** | **Stage 3** | **Stage 4** |
| Implement: Make an inventory of the current knowledge and skills of present workforce and contractors in the organization. Use a thorough specification of work. | Support: Use contractor already specialized in maintenance projects. Involve contractor in the LE team. | Drive: Share lessons learned on work packaging with other organizations. |
| The contractor, inexperienced with LEs and maintenance, contributes to a lower quality of the construction, a major scope and potential cost overruns due to the use of wrong insights. | The contractor executes predefined tasks, based on the current knowledge on the system’s performance | The contractor is familiar with the tasks needed for an LE and maintenance projects. The contractor’s insights are used to support the team. | Current workforce and contractors are able to execute the LE. The contractor is one of the sources of new ideas. |
5.3.2 Focus and priorities

In this section, the four stages of the decision element ‘focus and priorities’ are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to analyze the contents of each situation.

Definition of the strategies for each stage
Stage 1: No strategy – (Too) large scope of work and cost overruns.
Stage 2: Implementation strategy – Mitigate the effects of the current state of ‘facilities’ and ‘available technology’ of the asset organization, include drivers ‘Focus on initial quality’, ‘attention to detail’ and ‘innovative solutions’
Stage 3: Supporting strategy – Create internal support by connecting with the decision element ‘daily maintenance and operations’ and ‘cost and planning’.
Stage 4: Driving strategy - Ensure continuity and competitive advantage using the effects of ‘facilities’ and ‘available technology’, ‘Focus initial quality’, ‘attention to detail’ and ‘innovative solutions’

Case based evidence for the contents of the four stages
Stage 1: CASE 3 showed that workforce inexperienced with LEs can result in a larger scope, thus higher costs, than necessary.
Stage 2: Current facility management system mitigates the effects of the influences ‘obsolescence’, ‘norms and regulations’ and ‘demand and supply’. Use this to establish minimum requirements, as recommended by interviewee_2 & 4. Use the performance measurement system and analyze the local climate conditions and the process effects. Focus on the initial quality by performing quality assurance control on materials and quantity surveying to reassess the scope, as recommended by interviewee_5.
Stage 3: Connect with ‘daily maintenance and operations’ by adjusting the LE program to daily maintenance, as recommended by interviewee_1 & 5. Connect with ‘planning and costs’ by analyzing when the execution of tasks is needed, considering the costs and benefits. At this stage a large part of the scope is executed in daily maintenance and vital parts are restored in (calculated) planned shutdowns.
Stage 4: Interviewee_2 recommends to execute everything within the maintenance program, which is enabled by the current state of ‘facilities’ and ‘available technology’. Use multiple experiences to develop a clear and unambiguous guide for LEs. Build further on innovative solutions to improve the system’s performance.

Table 5-7 summarizes the contents of each stage. This will be part of the final framework.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement: Use facility management system to establish the minimum requirements. Use performance measurement system, quality assurance control and quantity surveying to establish the scope.</td>
<td>Support: Adjust the LE program to daily maintenance practices. Analyze when the tasks need to be executed considering the system’s actual performance.</td>
<td>Drive: Execute the LE within the maintenance program. Use multiple experiences to develop one single, clear and unambiguous guide for LEs.</td>
<td></td>
</tr>
<tr>
<td>(Too) large scope of work and cost overruns. Current knowledge is used and additional analyses are done to define the scope of work.</td>
<td>A large part of the scope is executed in daily maintenance, vital parts are restored in planned shutdowns.</td>
<td>Current state of ‘facilities’ and ‘available technology’ enables to include the LE into daily maintenance.</td>
<td></td>
</tr>
</tbody>
</table>
5.3.3 Planning and costs

In this section, the four stages of the decision element 'Planning and costs' are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to for contents of each situation.

Definition of the strategies for each stage
Stage 1: No strategy – No clear strategy for the execution of online and offline tasks.
Stage 2: Implementation strategy – Mitigate the effects of the current state of ‘facilities’ of the asset organization, avoid drivers 'postponing intervention'.
Stage 3: Supporting strategy – Create internal support by connecting with the decision element ‘focus and priorities’ and ‘daily maintenance and operations’.
Stage 4: Driving strategy - Ensure continuity and competitive advantage using the effects of the current state of ‘facilities’ of the asset organization and not 'postponing intervention'.

Case based evidence for the contents of the four stages
Stage 1: Interviewee_5 explains that the planning dilemma is whether to perform the tasks in an online or offline mode versus the costs. In the first stage, there is no specific strategy for the online or offline ratio.
Stage 2: Current facility management system identifies current and future needs of spares, tools and equipment, with regard to ‘obsolescence’, ‘norms and regulations’ and ‘demand and supply’. Use this to analyze the economic impact of performing the tasks in an online or offline mode as recommended by interviewee_1, interviewee_5 explains that shutting the system down could have major impact on the costs. On the other hand, performing the LE in an online mode can lead to safety issues and heat loss. Use the analysis to consider long term benefits versus the short-term planning, as recommended by interviewee_7.
Stage 3: Connect with the decision elements ‘focus and priorities’ and ‘daily maintenance and operations’ by planning which tasks are included in the LE scope and which task can be done in daily maintenance. Interviewee_5 recommends to balance the offline tasks with the marketing department to strengthen the link with the business. This is supported by Interviewee_6, who recommends to also use the planned shutdowns for maintenance of critical parts.
Stage 4: New facilities are developed in line with the asset organization’s demands. Parts can be replaced according to the system’s needs. Calculate when parts need to be replaced and share the planning tools and techniques with other asset organizations.

Table 5-8 summarizes the contents of each stage. This will be part of the final framework.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement: Use facility management system to analyze economic impact of online/offline ratio and consider long-term versus short term benefits.</td>
<td>Support: Plan which tasks are included in the LE scope and which task can be done in daily maintenance. Align offline tasks with marketing department.</td>
<td>Drive: Calculate when parts need to be replaced and share the planning tools and techniques with other asset organization.</td>
<td>New facilities are developed in line with the asset organization’s demands, which means that part can be replaced according to the system’s needs.</td>
</tr>
<tr>
<td>No clear strategy for the execution of online and offline tasks.</td>
<td>Online and offline tasks are balanced with the long term and short term benefits.</td>
<td>The majority of the offline tasks are done in planned shutdowns. These shutdowns are planned in line with the business.</td>
<td></td>
</tr>
</tbody>
</table>
5.3.4 Team composition

In this section, the four stages of the decision element ‘Team composition’ are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used for the contents of each situation.

Definition of the strategies for each stage
Stage 1: No strategy – No strategic considerations on who to include into the team.
Stage 2: Implementation strategy – Mitigate the effects of the current state of ‘workforce’ and ‘vertical integration’ of the asset organization, avoid driver ‘interference of disciplines’.
Stage 3: Supporting strategy – Create internal support by connecting with the decision element ‘contracting’.
Stage 4: Driving strategy - Ensure continuity and competitive advantage using the effects of the current state of ‘workforce’ and ‘vertical integration’ of the asset organization and no ‘interference of disciplines’.

Case based evidence for the contents of the four stages
Stage 1: Interviewee_1, 3, 4 & 5, all experienced with LEs, indicate that the different knowledge and skills needed for the LE are not combined properly. This results in interference of disciplines and an unrealistic scope of work.

Stage 2: Current workforce and contractors have sufficient operational knowledge and skills. To avoid interference of disciplines, interviewee_4 & 5 recommend to combine responsibilities of different disciplines in engineering, but also consult people involved in daily operations and maintenance. In order to do so, interviewee_3 suggests to interview the organization’s workforce. This way, engineering support is linked to the daily operation and maintenance practices. Interviewee_4 also suggests to create a team of locals and expats to share knowledge.

Stage 3: Connect with the decision element ‘contracting’ by involving the selected contractor(s) in the LE team. In this stage, the asset organization has developed more knowledge and skills on the system’s performance and is able to provide relevant information into the team. The combined perspectives enable a realistic scope of work. The LE team consists of contractor, permanent workforce and the supporting engineering disciplines.

Stage 4: Continue to optimize the LE team. Share knowledge on effective LE teams with other organizations (within the business).

Table 5-9 summarizes the contents of each stage. This will be part of the final framework.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>The knowledge and skills needed for the LE are not present or not combined properly, resulting in interference of disciplines and an unrealistic scope.</td>
<td>Implement: Interview current workforce and contractors and combine responsibilities in engineering.</td>
<td>Support: Involve the selected contractor in the LE team to ensure high quality and a realistic scope of work from all perspectives.</td>
<td>Drive: Continue to optimize the LE team. Share knowledge on effective LE teams with other organizations (within the business).</td>
</tr>
<tr>
<td>Current knowledge on system performance and maintenance practices are used for in team. The different disciplines in engineering do not interfere.</td>
<td>Team consists of contractor, permanent workforce and supporting engineering disciplines.</td>
<td>Other asset organizations are able to create effective teams for the LE.</td>
<td></td>
</tr>
</tbody>
</table>
5.3.5 Daily maintenance and operations

In this section, the four stages of the decision element 'Daily maintenance and operations' are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to analyze the contents of each situation.

Definition of the strategies for each stage
Stage 1: No strategy – Daily maintenance and operations are not considered for the LE.
Stage 2: Implementation strategy – Mitigate the effects of the current state of 'facilities' and 'available technology' of the asset organization, use driver 'triggers'.
Stage 3: Supporting strategy – Create internal support by connecting with the decision element 'focus and priorities', 'cost and planning' and 'performance measurement and reward system'.
Stage 4: Driving strategy - Ensure continuity and competitive advantage using the effects of the current state of 'facilities', and 'available technology' of the asset organization and the driver 'triggers'.

Case based evidence for the contents of the four stages
Stage 1: The objective of an LE is to restore the system's reliability, meaning that daily maintenance practices are not necessarily included in the LE plans.
Stage 2: Consider the LE versus the facility management system and the performance measurement system by including insights from the performance measurement system into the LE plans. This enables to include the implications for operations into the design. Interviewee 4 & 7 recommend to provide directions for future maintenance practices as result of the LE.
Stage 3: Connect with the decision element 'focus and priorities', 'cost and planning' and 'performance measurement and reward system' by adjusting the LE to daily maintenance practices, as recommended by interviewee 1. Increasing the ease of maintenance will have a positive impact on the system's availability, since the downtime of the system will be shorter. Interviewee 3 & 5 recommend collecting the preferences of people involved in daily operation. Certain aspects can already be incorporated in the daily operation and maintenance practices. Provide suggestions for performance measurement as result of the LE.
Stage 4: The LE is incorporated in daily maintenance practices. Continue to improve the reliability and maintainability of the system until the optimum availability is found. Table 5-10 summarizes the contents of each stage. This will be part of the final framework.

<table>
<thead>
<tr>
<th>TABLE 5-10: FOUR STAGES OF DAILY MAINTENANCE AND OPERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1</strong></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Daily maintenance and operations is not considered in the LE plans.</td>
</tr>
<tr>
<td>Insights and changes as result of the LE are stored in the performance measurement system. Recommendations for the execution tasks are provided.</td>
</tr>
</tbody>
</table>
5.3.6 Performance measurement and reward system

In this section, the four stages of the decision element ‘Performance measurement and reward system’ are established. First, a definition of the strategies for each stage is made using the implementation, supporting and driving strategies to arrive at the next stage or maturity level. After that, the recommendations from the multiple-case study are used to analyze the contents of each situation.

Definition of the strategies for each stage

Stage 1: No strategy – There is no performance measurement and reward system in the LE plans.

Stage 2: Implementation strategy – Mitigate the effects of the current state of ‘available technology’, ‘workforce’ and ‘vertical integration’ of the organization. Include ‘triggers’.

Stage 3: Supporting strategy – Create internal support by connecting with the decision element ‘daily maintenance and operations’.

Stage 4: Driving strategy - Ensure continuity and competitive advantage using the effects of the current state of ‘available technology’, ‘workforce’ and ‘vertical integration’ of the asset organization and the driver triggers.

Case based evidence for the contents of the four stages

Stage 1: There is no performance measurement system included in the plans for the LE.

Stage 2: Mitigate the effects of the current state of 'available technology', 'workforce' and 'vertical integration' of the asset organization, by including an inspection strategy into the LE program, as recommended by interviewee_1 & 4. The inspections need to be done before and after execution to measure the actual system performance. Interviewee_4 recommends to collect data and make a statistic overview of the system's performance over the years. This entails a performance measurement plan before the start of operation.

Stage 3: Connect with the decision element 'daily maintenance and operations' by linking the performance measurement system to the tasks resulting from the alignment between the LE and daily maintenance. Interviewee_4 & 5 recommend to include new technologies, such as risk based inspections (RBI), since it is difficult to start with new technologies when the system is in operation.

Stage 4: New performance measurement technologies enable a preventive or probabilistic response to failures. Therefore, a the LE can be included in daily maintenance practices. Implement these technologies in other asset organizations.

Table 5-11 summarizes the contents of each stage. This will be part of the final framework.

| TABLE 5-11: FOUR STAGES OF PERFORMANCE MEASUREMENT AND REWARD SYSTEM |
|-----------------|-----------------|-----------------|-----------------|
| Stage 1 | Stage 2 | Stage 3 | Stage 4 |
| No performance measurement and reward system included in the LE. | Implement: Use performance measurement system and available knowledge to define an inspection strategy as result of the LE. Include triggers for measuring performance. | Support: Link performance measurement system to the tasks resulting from aligning the LE with daily maintenance. Include new performance measurement technologies. | Drive: Implement the performance measurement technologies in other asset organizations |
| Clear performance measurement instructions are provided after the LE, including an explanation of the urge of execution of tasks. | Due to the new technologies the system's performances is measured effective and efficient. | New performance measurement technologies enable a preventive or probabilistic response to failures. The LE can be included in daily maintenance practices. |
5.4 Sub conclusions

This chapter’s goal was to embed the decisive influences on the SoS, as well as the success drivers within the SoS, into the decision-making process. The strategy for LE depends on the context of the LE, which related to the asset organization’s maturity. This section provides, in the first place, the answers to the sub questions as defined in the beginning of this chapter. In the second place, the resulting four stage framework for LEs is provided.

How can the success drivers and decisive influences be embedded into the decision-making process to maintain the system’s performance?

There are four decision elements for the asset organization enabling the system’s performance to be maintained. Each decision element includes decisions to respond to the decisive influences, as well as the success drivers for interventions. The decision elements for the asset organization are ‘workforce’, ‘facilities’, ‘available technology’ and ‘vertical integration’. These include the following influences:

- The decision element ‘workforce’ includes the influences ‘lack of knowledge and skills’, ‘effort’ and ‘insufficient capacity’.
- The decision element ‘facilities’ includes the influences ‘norms and regulations’, ‘demand and supply’ and ‘obsolescence’.
- The decision element ‘available technology’ includes the influences ‘knowledge and skills’, ‘effort’, ‘process effects on materials’, ‘local climate conditions’ and the success driver ‘triggers’.
- The decision element ‘vertical integration’ includes the influences ‘lack of knowledge and skills’, ‘initial quality of the system’ and the success driver ‘specification of work’.

The current state of each decision element determines the asset organization’s maturity regarding the ability to maintain the system’s performance. To reach the next maturity stage, the implementing, supporting and driving strategy is used for each decision element. This is done in the following way:

- The implementing strategy mitigates the effects of decisive influences from the context and includes success drivers for interventions.
- The supporting strategy creates support within the asset organization by connecting the decision elements.
- The driving strategy enables continuous improvement and enables other asset organizations (within the business) to benefit from the knowledge and skills to maintain the system’s performance.

The strategies for each decision element enable a description of the current state for each stage. The asset organization can use the descriptions to evaluate its own maturity of the decision-making process for maintaining the system’s performance.

What are the possible strategies for a lifetime extension?

In case that an asset organization is unable to maintain the system’s performance for the next lifespan, an LE is needed. The LE strategy can be defined based on the asset organization’s maturity stage regarding the ability to respond to the influences on the system’s performance and the decision-making process. The LE strategy for each stage consists of six decision elements. Each decision element includes decisions to respond to the current state of the asset organization, as well as the success drivers for interventions. The decision elements for LE are ‘contracting’, ‘focus and priorities’, ‘planning and costs’, ‘team composition’, ‘daily maintenance and operations’, and ‘performance measurement and reward system’. These include the following influences:
The decision element ‘contracting’ includes the current state of ‘workforce’ and ‘vertical integration’ of the asset organization and the success driver ‘specification of work’

The decision element ‘focus and priorities’ includes the current state of ‘facilities’ and ‘available technology’ of the asset organization and the success drivers ‘Focus on initial quality’, ‘attention to detail’ and ‘innovative solutions’

The decision element ‘planning and costs’ includes the current state of ‘facilities’ of the asset organization and avoids the driver ‘postponing intervention’.

The decision element ‘team composition’ includes the current state of ‘workforce’ and ‘vertical integration’ of the asset organization and avoids the driver ‘interference of disciplines’.

The decision element ‘daily maintenance and operations’ includes the current state of ‘facilities’ and ‘available technology’ of the asset organization and the success driver ‘triggers’

The decision element ‘performance measurement and reward system’ includes the current state of ‘available technology’, ‘workforce’ and ‘vertical integration’ of the asset organization and the success driver ‘triggers’.

The LE decision elements also include an implementing, supporting and driving strategy. These are based on the maturity stage of the asset organization. The strategies are used in the same way as for the asset organization.

Based on the answers to the sub questions it can be concluded that the strategy for the LE depends on the asset organization’s maturity regarding the ability to maintain the system’s performance. The approach for the LE varies between a project management approach to a maintenance management approach. For an immature organization a project management approach is needed for the LE, since there is limited knowledge on the system’s performance. In this case, the people involved in the LE are starting from scratch. For a mature organization a maintenance approach can be used for the LE, since the organization is able to maintain the system’s performance within the current practices.

Figure 5-5 shows the four stage framework as result of this chapter.
## Stage 2 - Assess

- **Drive:** Continue to improve the reliability and maintainability of engineering disciplines. Support: Involve the selected contractor in the LE team to ensure its involvement in the team.
- **Support:** Involve contractor in the LE team.
- **Implement:** Use performance measurement system to establish the team.

## Stage 3 - Plan

- **Drive:** Calculate when the amount of skilled and knowledgeable workforce is aligned with the system's needs. Support: Include new knowledge and skills in engineering.
- **Support:** Involve contractor in the LE team.
- **Implement:** Interview current workforce and contractors and provide recommendations for the tasks required.

## Stage 4 - Site Execution

- **Drive:** Share lessons learned on work to improve the knowledge and skills needed for the LE. Support: Include triggers for maintenance.
- **Support:** Include new knowledge and skills in engineering.
- **Implement:** Use facility management system to analyze economic and environmental factors.

### Table: Key Points

<table>
<thead>
<tr>
<th>Stage</th>
<th>Key Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assess</td>
</tr>
<tr>
<td>2</td>
<td>Plan</td>
</tr>
<tr>
<td>3</td>
<td>Site Execution</td>
</tr>
</tbody>
</table>

### Diagram: Four Stage Framework for Lifetime Extensions of Civil Structures

- **Stage 1:** Assess
  - **Drive:** Determine the knowledge and skills needed for the LE.
  - **Support:** Involve the selected contractor in the LE team.
  - **Implement:** Use performance measurement system to establish the team.

- **Stage 2:** Plan
  - **Drive:** Define the scope of work.
  - **Support:** Involve contractor in the LE team.
  - **Implement:** Use facility management system to establish the team.

- **Stage 3:** Site Execution
  - **Drive:** Calculate when the amount of skilled and knowledgeable workforce is aligned with the system's needs.
  - **Support:** Include new knowledge and skills in engineering.
  - **Implement:** Interview current workforce and contractors and provide recommendations for the tasks required.

- **Stage 4:** Site Execution
  - **Drive:** Share lessons learned on work to improve the knowledge and skills needed for the LE.
  - **Support:** Include triggers for maintenance.
  - **Implement:** Use facility management system to analyze economic and environmental factors.
6. VALIDATION & VERIFICATION: APPLICATION OF THE FRAMEWORK

This chapter's goal is to validate and verify the research results. The validation is done to assess whether the performed research leads to the right results. First, the research assumptions in relation with the empirical findings are discussed in section 6.1. The following research question will be answered:

G. How can the relationship between system performance and the decision-making process be described?

Second, the four stage framework is applied to CASE 4 in section 6.2. Due to the limited time available for the research, it is not possible to use the four stage framework in an asset organization and reflect on the practical implications. Therefore, the results of the four stage framework are compared with the civil asset master plan for CASE 4 developed by Shell. The recommended LE strategy for CASE 4 is already established the civil asset master plan. The benefits and limitations of using the four stage framework can be defined by comparing the results of both the framework and the master plan.

The verification in section 6.3 is done to assess whether the right research is performed. The practical need for the four stage framework is evaluated through expert interviews. After that, the implementation of the framework is discussed. These findings also result in an overview of further developments needed for the framework. In section 6.4, the findings are summarized and the validation and verification of the research is concluded.

6.1 Validation I: Evaluation of research assumptions

In this section the research assumptions are evaluated by reflecting on the findings from the empirical research. The relationship between the variables ‘decision-making’ and ‘system performance’ is reevaluated, because the description provided in chapter 2 is based on the literature research. In section 6.1.1 the research assumptions are validated against the empirical findings. In section 6.1.2 the limitations as result of the research scope, the data gathering process and the context specificity of Shell are discussed.
6.1.1 Research assumptions versus the empirical findings

The empirical research was based on a conceptual model that represents the relationship between the decision-making process and the system’s performance. In the mechanism it was assumed that the right input for the decision-making process would enable an LE of the system.

1. **Output of the SoS** - One of the assumptions was that the output of the conceptual model would be an LE. However, it was concluded in chapter 5 that the desired output of the SoS for the civil asset organization is maintaining the system's performance. The current state of the knowledge and skills on the right place needed to maintain the system’s performance enables an LE.

2. **Controllable causes of external influences** - In the conceptual model it was not assumed that there is a controllable cause of an external influence that has occurred. The influence ‘knowledge and skills’ was caused by the experience of the contractor, inspector and local management, as well as the continuity of the organization. The influence ‘initial quality of the system’ was indirectly caused by project management related aspect. These aspects were the pressure of planning and costs, the amount of insights in daily operations and the ability of the contractor to deliver the desired quality of the system. The causes were in all of the cases the result of the asset organization’s decisions made in earlier stage.

3. **Relationship interventions and inspections** – The quality of inspections and effectiveness of interventions were both influenced by the capacity in terms of workforce and the effort put into actions. It can be argued that both influences are a result of the decision-making process.

4. **Design life of the system** - It was assumed that the design life of the system was 20 years. However, Figure 4-3 in section 4.2.1 showed a remarkable increase of failures after 20 years. Since there is no data gathered on the specific time span of the increased failure occurred, it cannot be concluded that the increased amount of failures occurred because of the design life being ended. Besides, it was assumed that each component of the system has the same design life. Interviewee,5 explained that some components only have a design life of 5 to 10 years. The different design lives for each component were not considered in the research. Besides, the ended lifetime of one component might affect the lifetime of another component. The different design lives might affect the LE strategy, since the strategy is based on the assumption that the LE is executed after 20 years.

5. **System properties** - Degradation of the system as result of its properties was not included in the scope. Functional failures, such as tear, fatigue or collapse, arise as result of the material properties and constant loads on the construction (Coetzee, 1997). This applies to both the loads of the components on other components and the dead weights of each component. In the civil asset master plan the functional life of the asset is expressed as the load bearing capacity (Shell, 2013). The approach of the civil asset master plan is focused on the system properties, while this research is focused on the influences from the context on the system.

The differences between the conceptual model and empirical findings are the output of the SoS, controllable causes of external influences and the relationship between interventions and inspections. The differences are shown in Figure 6-1. These are not a limitation to the research findings, since these findings were the results of the empirical part of the research. However, the design life of the system and system properties are a limitation to the research findings. These two aspects are not included in the four stage framework.
When including the assumptions regarding the output of the SoS, the controllable causes of external influences and the relationship between interventions and inspections, the following sub question can be reevaluated:

**How can the relationship between the decision-making process and system performance be described?**

Based on the findings from the literature research, as well as the empirical research, it can be concluded that the decisions made are based on the knowledge and skills needed to maintain the system's performance in its context. More specific, the relationship between decision-making and system performance can be described as the following:

- The decision-making process is _influenced_ by direct _knowledge_ about the external influences ‘norms and standards’, demand and supply, obsolescence and indirect knowledge derived from the continuity of the organization and the experience of the contractor, inspector and local management.

- _Skills_ to identify the external influences local climate conditions, process effects on material and the initial quality of the system _determines_ the quality of inspections.

- _Knowledge_ derived from the inspections about the system performance, effort and the amount of workforce _influences_ the decision-making process, while at the same time the knowledge about ‘norms and standards’, demand and supply, obsolescence and indirect knowledge derived from the continuity of the organization and the experience of the contractor, inspector and local management influences whether or not an inspection is carried out.

- The decision-making process _influences_ the effectiveness of interventions through _knowledge_ about successful interventions. Successful interventions are characterized by triggers, a focus on the gaps of the initial quality of the system, a thorough specification of work, an attention to detail and spare part management. The interference of discipline, a lack of capacity, postponing the intervention and a lack of space to execute the work are drivers for failure.

- The _skills_ to execute the intervention _determines_ the change of the system’s performance.

These conclusions support the combined theories of Maslow (1954) regarding the consciousness and competence about failures, as well as the theory of Hayes and wheelwright (1984) regarding the relation between the organization and its context.
6.1.2 Research limitations

This research is limited by an inaccurate estimate of the actual design life and the exclusion of system properties outside the scope of research.

- **Design life** – The specific design life of the system and its components was assumed to be 20 years. Since there are strong indications that this estimate is inaccurate, it is not possible to state when the LE needs to be executed.

- **System properties** – The system properties, such as its dead weight, were not included in the scope of research. As result, these properties were not included in the four stage framework. The framework is limited to the external influences on the system’s performance.

There are also research limitations as result of the data gathering process. These are:

- **Recall bias** – The gathered data is based on the past experiences of the questionnaire respondents and the case interviewees. The risk of recall bias for the questionnaire is high, while the this risk is low for the interviews (Bowling, 2005). As result, the intensity and time of occurrence of failures caused by decisive influences might be inaccurate.

- **Coding of data** – The data derived from the interviews was analyzed using the coding method. This way, the relationships between the variables could be described on the level of the SoS. However, there is risk of the analysis becoming superficial and the fine-grained splitting of data may be overwhelming (Saldaña, 2012). This means that the important details could be overlooked.

- **Decisive influences without negative impact** – The questionnaire results showed that ‘accidents’ and ‘costs’ were not considered as decisive influences. In the author’s point of view, these aspects might need to be reconsidered. During the research, the author has experienced that there is a strict safety policy in Shell. It can be argued that the policy leads to a lower accident rate than in other companies. A lot of measurements are already taken and embedded in the organization. However, the fact that there is a mature response to potential accidents does not necessarily mean that the influence ‘accidents’ is not decisive for the performance of the asset organization. The influence ‘costs’ was not considered as decisive. For the influence to be decisive, the awareness about the influence was low, while the importance of influence was high. In that case, the influence was included in the research. It could be possible that all respondents were involved in cases where the incomes were aligned with the expenditures. However, it can be argued that the other influences, such as ‘norms and standards’, ‘knowledge and skills’ and ‘demand and supply’, are indirect cost drivers. This implies that one is aware of the costs, but unaware of the cost drivers.

The research limitations are a result of the scope, the data gathering process and the context of Shell. The scope definition leads to an inaccurate estimate of the actual design life and the exclusion of system properties. Shell’s civil asset master plan is more focused on the civil properties. Therefore, the next steps could be to include system properties in the framework, align the civil asset master plan with the framework or use the LE scope of the civil asset master plan instead of the decision element ‘focus and priorities’. The data gathering process could have led to data limited by recall bias and overlooked details. Performing the research in the context of Shell results in the decisive influences being Shell specific. Therefore, the results only apply for Shell. In order to apply the framework to other industries or organizations, another examination of decisive influences needs to be done.
6.2 Validation II: the framework versus current Shell practices

In this section the framework is applied to CASE 4 and its LE strategy is defined. This is done to identify the benefits and limitations of using the framework, as well as to define the future implications of the framework. First the current state of CASE 4 and the strategy for the LE are established. After that the findings are compared with the civil asset master plan for the LE developed by Shell. The civil asset master plan includes the draft version of the scope for LE, based on assessments done at the site. The assessments were focused on the equipment in combination with the LE and on the local management system, based on an in-house developed methodology. The results of the assessments were actions or strategies for improvement. These are compared with the LE strategies of the four stage framework.

6.2.1 Application to CASE 4

The four stage framework is applied to CASE 4 to define the LE Strategy. Based on the information provided by the interviewees involved in CASE 4 and documentation the current state of the asset organization can be described. For the decision elements 'workforce', 'facilities', 'available technology' and 'vertical integration' the structural changes are discussed to create a stable form of the asset organization. These structural changes are made to prepare the organization for the LE. Based on the stable form of the organization, the strategy for LE is defined. The description of the asset organization's current state is based on the interviewees involved in CASE 4 and assessments done at the site. The asset organization’s current state can be described as following:

- **Workforce** - There is insufficient knowledgeable and skilled workforce present. Interviewee_6 explains that, for example, people were not able to perform an inspection due to a lack of knowledge and skills, but that they were also eager to learn. Interviewee_8 confirms that during the last few years the inspection and maintenance skills have improved. However, it was concluded that the inspector training and development was incomplete, that not all inspectors were certified and that there were positions vacant (Shell, 2012b). In conclusion, the current state of workforce is 'Stage 1: Insufficient amount of skilled and knowledgeable workforce resulting in postponing or lacking execution of tasks.'

- **Facilities** – The civil department is responsible for ordering the facilities (Shell, 2013) Interviewee_5 explains that at CASE 4 there is a lot of obsolescence, which means that certain components cannot be replaced for new ones. In conclusion, the current state of facilities is ‘Stage 1: Uncontrolled management of facilities, resulting in obsolescence of parts and corrective responses to new norms and regulations or changed demands.’

- **Available technology** - Interviewee_6 has experienced that maintenance of civil technical components were often considered as second-class in priority. In 2014 the reliability centered maintenance (RCM) concept is implemented (Shell, 2014b). The program Pacer is present to store inspection data and recommendations, but the inspection data management system is ineffective (Shell, 2012b). Besides, the civil maintenance budget was underspent from 2008 to 2013 (Shell, 2013). In conclusion, developments to implement new technologies are made and a performance measurement is implemented, but not effective yet. When adding incentives or triggers to the current practices, the state of facilities will be 'Stage 2: The knowledge generated by the performance measurement system enables preventive measures.’

- **Vertical integration** - Interviewee_6 explains that external contractors built the plant 20 years ago, and after that the local organization had to maintain the plant themselves.
However, people at the site were not able to perform an inspection for example, due to a lack of knowledge and skills. At the moment, there is no maintenance contract strategy in place (Shell, 2013). In conclusion, the current state of vertical integration is ‘Stage 1: No contracting strategy used to maintain or restore the system’s performance.’

According to the four stage framework the state of ‘workforce, ‘facilities’ and ‘vertical integration’ is in maturity stage 1 and the state of ‘available technology’ is partly in stage 2. There is an unstable form of the asset organization at CASE 4. As result, corrective measures are taken to respond to the context. A stable form of the asset organization can be created in stage 2 to enable preventive measures. This entails structural changes regarding the workforce and the facilities. The following structural changes need to be made:

- **Implement:** Add (temporary) workforce with sufficient operational skills and knowledge. Train existing workforce. This enable the workforce to preventively respond to failures after the LE is completed.
- **Implement:** Develop facility management system to identify current and future needs of spares, tools and equipment. This enables the organization to respond preventively to new norms, regulations and changing demands.
- **A performance measurement system is present. Implement:** Triggers in current practices to ensure that the tasks documented in the performance measurement system are executed.
- **Implement:** Use contractor specialized in maintenance and make a clear specification of work. As result, the contractor supports the organization and is focused on maintaining the initial quality of the system.

Figure 6-2 shows the structural changes for the asset organization and the resulting LE strategy. In this stable form, the decision-making process after the LE is focused on mitigating the effects from the asset organization’s context.

![Figure 6-2: Structural Changes for the Civil Asset Organization and the Corresponding LE Strategy](image-url)
As result of the current state of the asset organization, the LE strategy includes:

- **Contracting** – Make an inventory of the current knowledge and skills of present workforce and contractors in the organization. Use a thorough specification of work for the tasks to be outsourced.
- **Focus and priorities** – Use facility management system to establish the minimum requirements. Use performance measurement system, quality assurance control and quantity surveying to establish the scope.
- **Planning and costs** – Use facility management system to analyze economic impact of online/offline ratio and consider long-term versus short term benefits.
- **Team composition** – Interview current workforce and contractors and combine responsibilities in engineering.
- **Daily maintenance and operations** – Use facility management and performance measurement system to document the changes made by the LE. Include triggers for maintenance.
- **Performance measurement system** - Use performance measurement system and available knowledge to define an inspection strategy as result of the LE. Include triggers to measure performance.

The LE strategy is adjusted to the state of the organization. This means that after the LE is executed, the civil asset organization should be able to maintain the system’s performance and respond preventively to failures.

### 6.2.2 The four stage framework versus the civil asset master plan

The structural changes for the asset organization and the LE strategy according to the framework are validated through the results derived from the methodology used in Shell. An assessment was done at CASE 4 in February 2012, resulting in an overview of areas for improvement in the site management systems and procedures and recommended actions for improvement. The data was gathered through a questionnaire, interviews with key staff and audits of site records. The results of this methodology are structured into a civil asset master plan (Shell, 2013). In this section, the civil asset master plan is compared with the results from applying the four stage framework to CASE 4. The evaluation of both methods is used to identify the benefits and limitations of the framework. First, the different approaches are compared based on the current state of the asset organization. After that, the recommended actions are compared with the strategies from the four stage framework.

**General approach**

The civil asset master plan is made to ensure an asset lifetime of 25+ years, while in the four stage framework the expected lifetime is not specified. However, it was assumed that one lifespan covers approximately 20 years. There are different topics formulated in the civil asset master plan. These topics represent the current state of the ‘civil organization effectiveness’ (Shell, 2013). Each topic contains a finding, objective and risk and a recommended action. Table 6-1 shows the overlap with the four stage framework.

<table>
<thead>
<tr>
<th>Shell (2013)</th>
<th>Corresponding decision element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leadership and Administration</td>
<td>Workforce / Facilities</td>
</tr>
<tr>
<td>Skill Resources, Training and Certification</td>
<td>Workforce</td>
</tr>
<tr>
<td>Procedures</td>
<td>Available technology</td>
</tr>
<tr>
<td>Materials and Degradation</td>
<td>Available technology</td>
</tr>
<tr>
<td>Inspection, engineering maintenance and repair</td>
<td>Available technology</td>
</tr>
</tbody>
</table>
The following differences between the civil asset master plan and the four stage framework regarding the approach are identified:

- There is no corresponding topic for the decision element vertical integration in the civil asset master plan. The skills and knowledge of the workforce is considered as both the employees and contractors. The relationship and distribution of these two types of workforce are not considered.
- The topics used by Shell are discussed more in detail than the states of the decision elements in the framework. Compared to the topics used by Shell there is more room for interpretation when using the framework.
- The civil asset master plan is focused on the structural changes needed for the asset organization. Many recommended actions overlap with the four stage framework. However, the changes for the LE are limited to an extensive discussion of the technical scope and planning. This corresponds with the decision elements 'focus and priorities' and 'planning and costs'.
- Safety not considered in the framework, while it is discussed in the civil asset master plan. This can be explained by Shell's strict safety policy to limit accidents. The policy is embedded in all the methodologies. As result the influence ‘accidents’ is not considered as decisive in the data analysis.

Structural changes for the asset organization

The current states and recommended actions of the civil asset master plan are summarized and compared with the states of the decision elements of the four stage framework. First, the current state of the decision element according to the civil asset master plan is defined. Second, the recommended actions are provided. After that, the recommended action is compared with the corresponding implementing strategy.

- **Workforce** – The current state of workforce was assessed through the topics 'leadership and administration' and 'skills resources, training and certification'. The findings are summarized as:
  - **Leadership and administration** – The civil discipline was inefficiently organized and the staffing inadequate. The focus of the discipline lies on managing day to day maintenance activities instead of asset integrity management.
  - **Skills resources, training and certification** – The management of civil asset integrity, reliability and design practices is considered as inadequate. There are also positions vacant.

The recommended actions regarding the workforce were to reconsider roles, to add at least one direct discipline technical engineer and to develop work processes to ensure competency of workforce and subcontractors. The recommended actions regarding training of workforce were to continue developing a training program for staff to increase the knowledge and experience and, in addition, to promote good open civil discussion forums within to discuss new civil techniques or product development within the industry.

The strategy of the four stage framework was to add (temporary) workforce with sufficient operational skills and knowledge and to train the existing workforce. It can be concluded that the strategy corresponds with the recommended action.

- **Facilities** – The current state of facilities was assessed through the topics 'Leadership and Administration'. The findings are summarized as:
  - **Leadership and administration** – The management system for Standards and Design Criteria was inadequate. Also the use of minimum standards for civil design criteria was inconsistent.
Recommended actions were to update the existing design criteria, implement a process to address the assessment of existing structures and assets against as-built, versus new design standards based on industry best practices. The strategy of the four stage framework was to develop a facility management system to identify current and future needs of spares, tools and equipment. Both the strategy and the topics are focused on a change of norms and standards. However, the framework is more focused on making an inventory of all the facility needs, while the civil asset master plan is more focused on design criteria.

- **Available technology** – The current state of facilities was assessed through the topics ‘Procedures’, ‘Inspection, engineering maintenance and repair’ and ‘Materials and Degradation’. The findings are summarized as:
  - **Procedures** – There is no involvement of the civil department in emergency response plans. Asset process and procedures are not documented integral to the emergency response plans.
  - **Inspection, engineering maintenance and repair** – The management of civil structures subject to fatigue was considered as inadequate. For example, there were no risk assessments done.
  - **Materials and Degradation** – Evidence was found that maintenance activities are appropriately tracked and monitored. However, the procedures for managing civil asset inspections were considered as inadequate.

The recommended actions were to implement work processes regarding emergency contingency plans, documenting the evaluation of the use of chemicals, to track inspections and to manage corrective actions when inspection tasks need to be extended.

The strategy of the four stage framework was to implement triggers in current practices to ensure that the tasks documented in the performance measurement system are executed. Despite that both the framework’s strategy and the recommended action are focused on the procedures, there are differences between the topics covered by the civil asset master plan and the framework’s strategy. The emergency or safety aspects whatsoever are not included in the framework. Not all procedures are in place to take action according to the master plan. Therefore, it cannot be stated whether there are triggers or incentives needed to execute the work.

- **Vertical integration** – There is no contracting strategy present.

The recommended actions were to implement a civil maintenance contract strategy to ensure the CASE 4 civil department operates efficiently and implement Key performance Indicators (KPI’s) to monitor contractor performance and effectiveness with a monthly review with the contractor management.

The strategy of the four stage framework was to use a contractor specialized in maintenance and to make a clear specification of work. Both the recommended action and the strategy of the framework are focused on developing a contracting strategy. The framework’s strategy is to use a contractor specialized in maintenance, while the civil asset master plan is focused on using KPI’s to track performance.

There is an overlap between the recommended structural changes of the civil asset master plan and the implementation strategies to reach stage 2 of the four stage framework. Most of the actions were focused on implementing processes. Compared to the descriptions of the four stage framework there is less room for interpretation in the topics used in the civil asset master plan.
The LE Strategy
The LE strategy is mainly focused on the technical scope and the planning and costs. However, also a part of the scope cover the actions needed due to a lack of maintenance. The decision elements contracting, team composition, daily maintenance and operations and performance measurement system were limited in the LE strategy. For each decision element, the recommended action according to the civil master plan is defined. After that, the recommended action is compared with the strategy according to the framework.

- **Focus and priorities** – In the civil master plan, the necessary LE interventions are described in detail for each asset. These are based on safety-critical elements derived from a bow-tie model that is used to assess hazards and consequences that may arise from an incident (Shell, 2012b).

  The strategy of the four stage framework was to use the facility management system to establish the minimum requirements and to use performance measurement system, quality assurance control and quantity surveying to establish the scope. The existing methodology used in Shell is focused on restoring the critical parts of the system to a safe level for operation, while the framework is focused on the amount of work, the costs and the quality of the results of the intervention. It can be argued that a safe level of operation is of primary importance. However, both methodologies do not have to interfere. Further research is needed to examine the most cost and quality effective way to establish the scope.

- **Planning and costs** – The (LE) maintenance tasks are recommended to be scheduled using the RBI principles. An overview was made of the online and offline tasks for the fabric LE.

  The strategy of the four stage framework was to use facility management system to analyze economic impact of online/offline ratio and to consider long-term versus short term benefits. These aspects are not considered in the civil asset master plan. The strategy is focused on the long term costs and benefits of the planning, while the master plan is focused on the possibilities and limitations of the tasks that need to be executed. It can be argued that the framework's strategy is a follow up of dividing the offline and online tasks.

- **Team composition** – The responsibilities for the engineering, maintenance and project department are described for the LE. Besides, it was already explained that the data was gathered through a questionnaire, interviews with key staff and audits of site records questionnaire, interviews with key staff and audits of site records.

  The strategy of the four stage framework was to interview current workforce and contractors and combine responsibilities in engineering. This corresponds with the findings from the civil asset master plan. However, it is not described that the responsibilities in engineering are combined to avoid interference.

- **Daily maintenance and operations** – The recommended action as result of the LE was to develop an understanding of the maintenance history to the critical assets and ensure updated in the PACER maintenance program.

  The framework's strategy is to use facility management and performance measurement system to document the changes made by the LE and to include triggers for maintenance. The strategy corresponds with the recommended action of the civil asset master plan.

- **Performance measurement** – The recommended action was to provide guidance on ensuring maximum efficiency out of Risk Based Inspection (RBI) system to ensure future inspection methodology takes into account learnings from within the Shell Group or from the industry. The framework's strategy is to use performance measurement
Towards a lifetime extension strategy for civil structures

system and available knowledge to define an inspection strategy as result of the LE and to include triggers for performance measurement. The strategy corresponds with the recommended action of the civil asset master plan.

For the LE, the civil asset master plan is for a larger part focused on the civil technical aspects and for the planning on the possibilities and limitations of the tasks that need to be executed. The framework is more focused on available knowledge and skills for the LE strategy. Besides, the planning is more focused on the on the long term costs and benefits of the planning.

A large part of the scope is covered by non-LE actions. Some of the (corrective) actions for the civil technical aspects were the result of a lack of maintenance. This can be explained by the current state of the organization, which corresponds with stage 1 of the four stage framework. As result of this state, many corrective measures will be taken.

6.2.3 Identified benefits and limitations of the framework

In this section, the benefits and limitations of using the framework are summarized. The summary is based on the comparison of strategies between the four stage framework and the civil asset master plan.

The benefits are:

- The LE strategy is based on the current state of the asset organization. More specific, the LE is placed in the context of the possibilities and limitations of the people working in the asset organization.
- The implications for the asset organization as result of the LE regarding daily maintenance and performance measurement are included in the LE strategy. This way, people working in daily maintenance have the knowledge and skills needed to maintain the 'new' system.
- Strategic considerations are made about the people involved in the LE. The four stage framework includes the relationship with the contractor and how the knowledge and skills of the workforce and engineering support are combined.

The limitations are:

- The descriptions of the stages in the four stage framework are not detailed. Compared to the civil asset master plan there is more room for interpretation.
- Safety aspects are not considered in the four stage framework.
- The description of the technical scope in the states of the decision element 'focus and priorities' seems insufficient, compared to the civil asset master plan.
- The comparison with the civil asset master plan only covers stage 1 and 2 of the framework.

Before the implementation further development of the four stage framework is needed for the descriptions of the stages, safety aspects and the technical scope. The implications for implementations are discussed in section 6.3.2.

6.3 Verification: The practical need of the four stage framework

Within Shell, specifically in the area of civil structures, there was little knowledge about the decision to include in the LE preparation. The framework was discussed with two interviewees from the Operational Excellence (OE) department and one interviewee from the Civil Structures and Offshore (CSO) department of Shell. In Operational Excellence the focus lies on the asset's reliability, unit operating costs, technical integrity and excellence in well and reservoir management (Shell, 2014c). Table 6-2 provides a description of the interviewees.
TABLE 6-2: DESCRIPTION OF INTERVIEWEES

<table>
<thead>
<tr>
<th>#</th>
<th>Perspective</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Civil engineering</td>
<td>Involved in the development of the civil asset master plan, &lt; 10 years work experience in Shell</td>
</tr>
<tr>
<td>10</td>
<td>Operational excellence</td>
<td>Involved in the development of Shells operation management tools, &lt;10 years working experience, &gt; 5 years in Shell, experiences from other companies &amp; universities.</td>
</tr>
<tr>
<td>11</td>
<td>Operational excellence</td>
<td>Production performance lead &amp; Operational Excellence coordinator at Shell, &lt;10 years work experience in Shell</td>
</tr>
</tbody>
</table>

All of the interviewees are considered as an expert, since they have more than 10 years of work experience. In section 6.3.1 the opinions of the interviewees about the usability of framework are provided for the entire organization, as well as specifically the area of civil engineering. In section 6.3.2 the implications for implementation are discussed. In section 6.3.3 the four stage framework is evaluated form a wider perspective.

6.3.1 Usability of the framework

The framework can be linked to the existing methodologies developed in Shell, such as the continuous improvement process. The fourth stage of the four stage framework can also be seen as a continuous improvement of the current practices. Both interviewee_10 and 11 indicate that the steps per stage seem logical. Interviewee_10 explains that a similar kind of framework is in development in the OE department. He indicates that the four stage framework can be used at the interface between the ‘asset-2-cash’ phase and the ‘abandonment’ phase. This is comparable to the operation and decommissioning phase within the construction industry. In his opinion, the four stage framework can be used when it is concluded that there is more gas in the field near the plant, which is done after a thorough analysis and calculations. The next step is to explore the options and scope for the plant’s lifetime extension. This does not mean that the LE actually takes place.

Interviewee_11 states that, in order to use the framework, the states of each state should be defined more in detail and measured quantitatively. His specific remarks include the following:

- **Facilities, stage 4** - Focus on obsolescence for leverage. Another oil company within negotiated with the vendor. As result spares, tools and equipment are developed in accordance to the demands of the company.
  
  This statement supports the contents of the four stage framework.

- **Focus and priorities, all stages** – Focus on the minimum technical solution. This means that interventions are done with a minimum amount of technological changes. Integrate lessons learned in other assets and causal learning to establish the scope of work.
  
  This statement supports the contents of the four stage framework, compared to the existing methodology.

- **Team composition, all stages** – There are side conditions needed for optimal team effectiveness. Besides the LE team, also a technical review team is needed to challenge the proposed solutions from the team. This way a ‘managed conflict’ is created, which enhances the innovative and creative solutions. In conclusion, to come up with creative and innovative solutions, multidisciplinary knowledge and skills are needed as well as a counter party to challenge the ideas.

- **Daily maintenance and operation** - Increasing the ease of maintenance should be accompanied by quantifiable measures to explain exactly to what extent time spent on maintenance will be decreased and the availability of the plant will be increased. There are already tools within available within Shell to calculate these aspects.
- Planning and costs, stage 3 - A shutdown planning tool can be used to plan the offline and online tasks.
- Contracting - Contractors specialized in lifecycle extensions do also exist.

Based on the opinions of interviewee_10 and 11, it can be concluded that there is potential for the framework to be used in Shell. Further research is needed for the inclusion of calculations and measurable indicators for the stages of the framework.

“Within Operational Excellence we are currently developing a similar kind of framework, so this framework could definitely be used within Shell. The framework fulfills the practical needs and the steps for improvement are easy and tangible.”

Interviewee - Production performance lead & Operational Excellence coordinator at Shell

However, in the area of civil structures there is a stronger need for the framework than in OE. As concluded in section 6.2.2 the framework’s suggested structural changes for the asset organization overlap with the current practices. However, the current practices for the LE are mainly focused on the technical scope of work and to a smaller extend to the planning. Interviewee_1 explains that in civil engineering there is limited awareness about all the decisions for an LE. Using the framework enables to also include the decision elements outside the technical scope. Section 6.3.2 will focus on the framework in the area of civil structures.

6.3.2 Implications for implementation

The implementation of the framework is most relevant in the area of civil structures. This applies to the civil maintenance and operation teams or organizations located at the asset, as well as the civil structures team in Projects and Technology (P&T) of Shell. The steps for implementation were discussed with Interviewee_1, responsible for asset integrity management in civil engineering at P&T. He has experienced that more than 50% of the technical scope of LEs is related to civil structures. There is a need for a reduction of this scope.

Before the implementation can take place, the following steps need to be made:

- Make an accurate estimate the actual design life of the assets.
- Include system properties in the framework, align the civil asset master plan with the framework or use the LE scope of the civil asset master plan instead of the decision element ‘focus and priorities’.
- Provide more detailed descriptions of the stages. In order to do so, it was recommended to examine measurable indicators, for example failure and cost reduction per stage and the latest moment to intervene in the system’s performance.

After the steps are made, the four stage framework can be implemented in an actual case. The civil engineers from P&T should take the lead for implementation, in the author’s point of view, since the need for the result of the research came from the civil engineers at P&T. The civil engineers from P&T need to visit the site to discuss the framework with the civil engineers from the civil asset organization located at the site. Together they can evaluate the current state of maturity of the civil asset organization. After the current state is identified, the desired maturity stage can be established. This will lead to a set of structural changes for the civil asset organization and the LE strategy. The LE strategy can be specified in detail after agreements are made about the planning of the structural changes for the civil asset organization. Interviewee_1 explains that in practice, the civil asset organization is aware of the coming LE long before the LE actually takes place. There is already room for structural changes in the daily operation. However, it appears that these changes are
postponed until the start of the LE. Therefore, the agreement for the structural changes is highly important for the successful implementation of the framework. The framework can be used for other sites and disciplines after it is successfully implemented in the first case. The civil asset organizations located at the sites should eventually take the lead in using the framework.

### 6.3.3 The four stage framework from a wider perspective

In the area of civil engineering in the oil and gas industry or the literature there was little knowledge about LEs. The four stage framework for LEs provides more understanding about the knowledge and skills needed for the LE, as well as the implications of the LE for daily maintenance and operation. Using this framework enables to strategically use the short-term event of an LE for increasing the long-term operation and maintenance effectiveness.

The four stage framework for LEs is limited by civil structures in the oil and gas industry. These structures are often owned by private companies. The design life is similar to the functional life, based on an estimate of the economic life. Because of the predefined functional life, civil maintenance is neglected and priority is given to system parts of vital importance, such as rotating equipment and IT systems. As result, civil assets are maintained correctively, and in some cases preventively. The current state of the civil asset organization is stage 1 or 2 in the four stage framework. Therefore, the LE strategy is project based and civil aspects cover the larger part of the technical scope. This would be the same for offshore structures having a similar design and functional life, but possibly other decisive influences.

The civil structures in the public sector, such as roads and bridges, have a longer functional life than its design life in contrast to the civil structures in the oil and gas industry. Besides, there are less other system parts of vital importance. Therefore, maintenance is often already considered during the design phase. As result, an internal support system to maintain the asset can be created and the civil asset organizations can have a current state of stage 3 in the framework. This implies that an LE can be included in the daily (non-routine) maintenance practices.

Compared to civil assets, floating assets can have a longer functional life, since the economic life can be renewed by moving the asset to another gas field. The asset can be designed for a longer lifespan or an internal support system for maintenance of the asset can be created, corresponding with stage 3 of the framework. The LE can be included in the daily maintenance practices.

In most of the cases the economic life of the civil structure turned out to be longer than planned. Therefore, it can be argued that for civil structures in the oil and gas industry a similar approach can be used as for civil structures in the construction industry. This implies that the focus lies on bringing the state of the civil asset organization to the 3rd stage of the framework. The framework’s implementation and support strategies can be applied during the civil structure’s lifespan, so that the LE can be included in the daily (non-routine) maintenance practices. Main drivers are the knowledge, skills and procedures needed for maintenance. By evaluating the current state of the asset organization, one can focus on improving these knowledge, skills and procedures. As result, the technical scope of the LE can be downsized, while the intensity of daily maintenance practices increases.
6.4 Sub conclusions

This chapter's goal was to validate and verify the four stage framework and to evaluate the research assumptions. First, the research assumptions were evaluated. This resulted in an overview of research limitation. Second, the benefits and limitations of using the four stage framework compared to the existing methodology used in Shell were identified. Third, the implications of using the framework are discussed.

As result of the scope, the data gathering process and the Shell specific context of the research, the following limitations are identified:

- **Design life** – There are strong indications that the estimated design life of 20 years is inaccurate. As result, it is not possible to state when the LE needs to be executed.
- **System properties** – The research is limited to the external influences on the system’s performance. As result, system properties were not included in the four stage framework.
- **Recall bias** – There is a high risk of recall bias the questionnaire data. As result, the intensity and time of occurrence of failures caused by decisive influences might be inaccurate.
- **Coding of data** – The data derived from the interviews was coded and placed into categories. As result, the important details could be overlooked.
- **Decisive influences without negative impact** – The influences ‘accidents’ was not considered as decisive. Shell's strict safety policy might limit the impact of the influence. As result, it cannot be concluded that the influence ‘accidents’ is not decisive. The influence ‘costs’ was not considered as decisive. The respondents could be aware of the costs, but not aware of the cost drivers. As result, it cannot be concluded that the influence ‘costs’ is not decisive.

Compared to the civil asset master plan it can be concluded that using the four stage framework has the following benefits:

- The LE strategy is based on the current state of the asset organization. More specific, the LE is placed in the context of the possibilities and limitations of the people working in the asset organization.
- The implications for the asset organization as result of the LE regarding daily maintenance and performance measurement are included in the LE strategy. This way, people working in daily maintenance have the knowledge and skills needed to maintain the ‘new’ system.
- Strategic considerations are made about the people involved in the LE. The four stage framework includes the relationship with the contractor and how the knowledge and skills of the workforce and engineering support are combined.
The limitations are:

- The descriptions of the stages in the four stage framework are not detailed. Compared to the civil asset master plan there is more room for interpretation.
- Safety aspects are not considered in the four stage framework.
- The description of the technical scope in the states of the decision element ‘focus and priorities’ seems insufficient, compared to the civil asset master plan.

Based on the interviews with Shell employees, it can be concluded that there is potential for the four stage framework to be used on an organization wide level. However, there is a more urgent need for the framework in the area of civil structures. Before the implementation, the following aspects need to be examined:

- Make an accurate estimate the actual design life of the assets.
- Include system properties in the framework, align the civil asset master plan with the framework or use the LE scope of the civil asset master plan instead of the decision element ‘focus and priorities’.
- Provide more detailed descriptions of the stages. In order to do so, it was recommended to examine measurable indicators, for example failure and cost reduction per stage and the latest moment to intervene in the system’s performance.

After the steps are made, the four stage framework can be implemented in an actual case. The civil engineers from P&T need to take the lead and visit the site to discuss the framework with the civil engineers from the civil asset organization located at the site. After the current state is identified, the desired maturity stage can be established. This will lead to a set of structural changes for the civil asset organization and the LE strategy. The LE strategy can be specified in detail after agreements are made about the planning of the structural changes for the civil asset organization. The framework can be used for other sites and disciplines after it is successfully implemented in the first case. The civil asset organizations located at the sites should eventually take the lead in using the framework.

From a wider perspective, it can be stated that in most of the cases the economic life of the civil structure turned out to be longer than planned. Therefore, a similar approach can be used for civil structures in the oil and gas industry as for civil structures in the public sector. The focus lies on bringing the state of the civil asset organization to the 3rd stage of the framework by applying implementation and support strategies during the civil structure’s lifespan. Main drivers are the knowledge, skills and procedures needed for maintenance. By evaluating the current state of the asset organization, one can focus on improving these knowledge, skills and procedures. As result, the technical scope of the LE can be downsized, while the intensity of daily maintenance practices increases.
7. CONCLUSION & RECOMMENDATIONS

This chapter provides the answer to the central question. The answer is underpinned through an evaluation of the answers provided by the sub questions. This will be done in section 7.1. In section 7.2 the research limitation are discussed. After that recommendations for implementation and future research are provided in section 7.3.

7.1 Conclusion

The general conclusion of the research is provided by the answer to the central question. This is done in section 7.1.1. The general conclusion is supported by the evidence from the sub conclusions, which is provided in section 7.1.2.

7.1.1 General conclusion

The economic lifetime of the civil structures in the oil and gas industry is determined by the available resources and the market. Due to changing external demands the civil structures often have a longer economic lifetime than its technical lifetime. Maintenance of civil structures during their lifespan is of second-order priority. However, in case of an economic LE, the larger part of the technical scope of the LE is determined by civil structures. Based on the results, the following central question can be answered:

How can knowledge about the influences on a civil structure's lifespan be embedded in the decision-making process for a lifetime extension?

Knowledge about the influences on a civil structure’s lifespan can be embedded by using the four stage decision-making framework created in this research. The framework is presented in Figure 5-5.

The relationship between system performance and the decision-making process is influenced by the amount of knowledge about the decisive influences on the system’s performance and determined by the amount of skills needed to maintain the system’s performance. The current state of the civil asset organization is determined by the combined amount of knowledge and skills present at the location. A civil asset organization can use the framework to evaluate its own maturity regarding the knowledge, skills and the procedures needed to maintain the civil structure. The LE strategy can be selected based on the civil asset organization’s maturity. The LE of a mature organization is defined by a technical scope consisting of multiple smaller tasks, while the intensity of daily maintenance practices is increased.
The LE approach varies between a project management approach and a maintenance management approach. For an immature organization a project management approach is needed for the LE, since there is limited knowledge about the system’s performance. In this case, the people involved in the LE are starting from scratch. For a mature organization a maintenance approach is used for the LE, since the organization is able to maintain the system’s performance within the current practices. Furthermore, the organization has more knowledge about the actual performance of the system.

Based on the organization’s maturity one can embed knowledge about the influences by:

- Using implementing strategies to mitigate the effects of decisive influences from the context. The strategies include success drivers for interventions.
- Using supporting strategies to create support within the asset organization
- Using driving strategies to enable continuous improvement and to enable other asset organizations (within the business) to benefit from the organization’s knowledge and skills.

The strategies can be used for each decision element for the civil asset organization. The decision elements included the subjects to make decisions about. For the organization these are the workforce, the facilities, the available technology and the vertical integration or relationship with contractors. Using the strategies results in structural changes creating a stable maturity level of the asset organization. Based on the stable form of maturity, the corresponding LE strategy can be applied. The LE strategy also consists of a set implementing, supporting or driving strategies corresponding with the state of the civil asset organization.

Using the framework has its advantage over the existing methods used, because the LE is placed in the context of the possibilities and limitations of the people working in the asset organization. More specific, the implications for the civil asset organization as result of the LE regarding daily maintenance and performance measurement are included in the LE strategy. This way, people working in daily maintenance have the knowledge and skills needed to maintain the ‘new’ system. Furthermore, the four stage framework includes the relationship with the contractor and provides steering to combine the knowledge and skills of the workforce and engineering support.
7.1.2 Supporting sub conclusions

The general conclusion is supported by the answers to the sub questions. These are discussed below.

*How can the relationship between system performance and the decision-making process be described?*

The relationship between system performance and the decision-making process is influenced by the amount of knowledge about the system’s performance and determined by the amount of skills needed to maintain the system’s performance.

- The decision-making process is **influenced** by direct **knowledge** about the external influences 'norms and standards', demand and supply, obsolescence and indirect knowledge derived from the continuity of the organization and the experience of the contractor, inspector and local management.

- **Skills** to identify the external influences local climate conditions, process effects on material and the initial quality of the system **determines** the quality of inspections.

- **Knowledge** derived from the inspections about the system performance, effort and the amount of workforce **influences** the decision-making process, while at the same time the knowledge about 'norms and standards', demand and supply, obsolescence and indirect knowledge derived from the continuity of the organization and the experience of the contractor, inspector and local management influences whether or not an inspection is carried out.

- The decision-making process **influences** the effectiveness of interventions through **knowledge** about which interventions are successful. Successful interventions are characterized by triggers, focus on the gaps of the initial quality of the system, a thorough specification of work, attention to detail and spare part management. Interference of discipline, capacity, postponing the intervention and a lack of space to execute the work are drivers for failure.

- The **skills** to execute the intervention **determines** the change of the system's performance.

*What are the decisive influences from the context affecting system performance?*

The starting point for assessing the nature of influences on system performance is the initial quality of the design. It can be concluded that four kinds of 'design and construction errors' are limiting the initial quality of the system. These errors are:

- **Initial design** - The initial design is not fit for purpose for local climate conditions, because of the use of wrong materials. This type of error occurs at sites near the coast and along the shore. Main reason for failure during the plant's lifespan is related to the saline environment rather than tropical conditions.

- **Process effects on materials** - Process effects on materials are underestimated due to weak spots and insufficient attention to details. One of the reasons for this is the pressure on the planning during the execute phase.

- **Focus on low project costs** - The focus on low costs during the design and execute phase, resulting in short term benefits instead of long term benefits. However, there seems to be a tendency to focus more and more on long term benefits.

- **Inability of contractor to deliver the quality** - The contractor is not able to deliver the desired quality. The initial quality of the system is dependent on a specification in which this quality level is established.
What are the decisive influences from the context affecting the decision-making process?
There are four external influences on decision-making processes. These are:

- **Demand and supply of gas** - A change compared to the initial prognosis for the amount of gas is the driver for a LE. In case an LE is needed, but the second economic life is shorter than the first economic life, the LE can be used to downscale the plant through the concept of de-complexing.

- **New norms and standards** - The dilemma with new norms and standards is that, on the one hand the adoption of new norms and standards provides the possibilities to improve the performance of the system, but on the other hand it can lead to a large scope and investment. The decision to upgrade the plant in order to comply with the new norms is dependent on the economic value of the site. In case of a decrease of economic value, it is not worth the investment.

- **Knowledge and skills** - In all of the cases there were periods during the lifespan that there was a lack of knowledge at the sites. Main reasons were a continuous change of management, the policy to embed local workforce and the limited experience of the contractors. The latter is related to a ‘greenfield’ approach, which can lead to a major scope and cost indication. A lack of knowledge and skills leads to a lack of attention to civil structural aspects and the wrong priorities.

- **Technological change** - Technological change is related to obsolescence of components. Some parts of the plant have a shorter design life than other parts. Over time there are often new technologies developed. This results in replacement of sub systems by new types of systems.

What are the drivers determining the success of inspections and interventions?
Successful inspections and interventions are characterized by the following drivers:

- **Focus on initial quality** - The focus on the initial quality of the system involves the identification of the external influences on system performance. This way the gaps between the initial quality of the system and its operating context can be resolved.

- **Unique and innovative solutions** - Using unique and innovative solutions enable effective interventions. The solutions are not necessarily high-tech solutions.

- **Triggers** - Triggers are needed to avoid postponing, lacking execution or putting insufficient effort into the execution of tasks. Multiple cases showed that without an incentive or trigger, the maintenance tasks were reactive of nature and the scope for the LE was larger than needed.

- **Resource management** - Proper resource management includes ensuring that there is a sufficient amount of spare parts, tools and equipment are present so that the intervention can take place.

There were also drivers for failure in found in the evaluation of inspections and interventions:

- **Postponing or lacking execution of work** - Postponing, or even lacking execution of (preventive) maintenance tasks, resulted in reactive maintenance.

- **Lack of knowledge and skills** - A lack of knowledge and skills, or a small capacity of the organization, resulted in postponing or lacking the execution of work.

- **Interference** - Interference among different disciplines, or lack of space, leads to inefficient execution of the work. It seems like the disciplines are focused on their own work and that there is a lack of understanding of the broader view on the LE.

In order to ensure successful interventions a sufficient amount of workforce with adequate knowledge and skills are needed. These are needed to identify the gap between the initial quality of the system and its operating context and to come up with creative solutions.
How can the success drivers and decisive influences be embedded into the decision-making process to maintain the system’s performance?

There are four decision elements for the asset organization enabling the system’s performance to be maintained. Each decision element includes decisions to respond to the decisive influences, as well as the success drivers for interventions. The decision elements for the asset organization are ‘workforce’, ‘facilities’, ‘available technology’ and ‘vertical integration’. These include the following influences:

- The decision element ‘workforce’ includes the influences ‘lack of knowledge and skills’, ‘effort’ and ‘insufficient capacity’.
- The decision element ‘facilities’ includes the influences ‘norms and regulations’, ‘demand and supply’ and ‘obsolescence’.
- The decision element ‘available technology’ includes the influences ‘knowledge and skills’, ‘effort’, ‘process effects on materials’, ‘local climate conditions’ and the success driver ‘triggers’.
- The decision element ‘vertical integration’ includes the influences ‘lack of knowledge and skills’, ‘initial quality of the system’ and the success driver ‘specification of work’.

The current state of each decision element determines the asset organization’s maturity regarding the ability to maintain the system’s performance. To reach the next maturity stage, the implementing, supporting and driving strategy is used for each decision element. This is done in the following way:

- The implementing strategy mitigates the effects of decisive influences from the context and includes success drivers for interventions.
- The supporting strategy creates support within the asset organization by connecting the decision elements.
- The driving strategy enables continuous improvement and enables other asset organizations (within the business) to benefit from the knowledge and skills to maintain the system’s performance.

The strategies for each decision element enable a description of the current state for each stage. The asset organization can use the descriptions to evaluate its own maturity of the decision-making process for maintaining the system’s performance.

What are the possible strategies for a lifetime extension?

In case that an asset organization is unable to maintain the system’s performance for the next lifespan, an LE is needed. The LE strategy can be defined based on the asset organization’s maturity stage regarding the ability to respond to the influences on the system’s performance and the decision-making process. The LE strategy for each stage consists of six decision elements. Each decision element includes decisions to respond to the current state of the asset organization, as well as the success drivers for interventions. The decision elements for LE are ‘contracting’, ‘focus and priorities’, ‘planning and costs’, ‘team composition’, ‘daily maintenance and operations’, and ‘performance measurement and reward system’. These include the following influences:

- The decision element ‘contracting’ includes the current state of ‘workforce’ and ‘vertical integration’ of the asset organization and the success driver ‘specification of work’.
- The decision element ‘focus and priorities’ includes the current state of ‘facilities’ and ‘available technology’ of the asset organization and the success drivers ‘Focus on initial quality’, ‘attention to detail’ and ‘innovative solutions’.
- The decision element ‘planning and costs’ includes the current state of ‘facilities’ of the asset organization and avoids the driver ‘postponing intervention’.
The decision element 'team composition' includes the current state of 'workforce' and 'vertical integration' of the asset organization and avoids the driver 'interference of disciplines'.

The decision element 'daily maintenance and operations' includes the current state of 'facilities' and 'available technology' of the asset organization and the success driver 'triggers'.

The decision element 'performance measurement and reward system' includes the current state of 'available technology', 'workforce' and 'vertical integration' of the asset organization and the success driver 'triggers'.

The LE decision elements also include an implementing, supporting and driving strategy. These are based on the maturity stage of the asset organization. The strategies are used in the same way as for the asset organization.

7.2 Limitations

The results of the research are compared with the research assumptions. The comparison resulted in research limitations related to the scope of the research, the data gathering process and the Shell specific context of the research. The following limitations are identified:

- **Design life** – There are strong indications that the estimated design life of 20 years is inaccurate. As result, it is not possible to state when the LE needs to be executed.

- **System properties** – The research is limited to the external influences on the system's performance. As result, system properties were not included in the four stage framework.

- **Recall bias** – There is a high risk of recall bias the questionnaire data. As result, the intensity and time of occurrence of failures caused by decisive influences might be inaccurate.

- **Coding of data** – The data derived from the interviews was coded and placed into categories. As result, the important details could be overlooked.

- **Decisive influences without negative impact** – The influences 'accidents' was not considered as decisive. Shell's strict safety policy might limit the impact of the influence. As result, it cannot be concluded that the influence 'accidents' is not decisive. The influence 'costs' was not considered as decisive. The respondents could be aware of the costs, but not aware of the cost drivers. As result, it cannot be concluded that the influence 'costs' is not decisive.

The four stage framework is compared with the results of the civil master plan developed by Shell. The civil master plan included the recommended actions for the LE. Compared to the civil asset master plan it can be concluded that the four stage framework has the following limitations:

- The descriptions of the stages in the four stage framework are not very detailed. As result, there is room for interpretation.

- Safety aspects are not considered in the four stage framework.

- The description of the technical scope in the states of the decision element 'focus and priorities' seems insufficient, compared to the civil asset master plan.
7.3 Recommendations

The recommendations as result of this research are divided in recommendations for further development of the framework and recommendation for future research. For the recommendations regarding the framework a recap on the findings is provided in section 7.3.1. The research directions and the possible research questions are discussed in section 0.

7.3.1 Recommendations for implementation

In order to make the framework more fit-for-purpose, further improvements should be made in the specific strategies and descriptions of current situation. After that, the framework can be embedded in the current for further optimization.

The next steps for implementation are:

- **Actual design life** - There are strong indications that the estimated design life of 20 years is inaccurate. Therefore, an accurate estimate the actual design life of the assets needs to be made.
- **System properties** - The system properties, such as the system's dead weight, were not included in the research. It should be examined whether to include system properties in the framework, align the civil asset master plan with the framework or use the LE scope of the civil asset master plan instead of the decision element 'focus and priorities'.
- **Measurable indicators** - In order to evaluate on the current state of the civil asset organization, more detailed descriptions of the framework's stages are needed. In order to do so, it was recommended to examine measurable indicators, for example failure and cost reduction per stage and the latest moment to intervene in the system's performance.

After the steps are made, the four stage framework can be implemented in an actual case. The civil engineers from P&T need to take the lead and visit the site to discuss the framework with the civil engineers from the civil asset organization located at the site. After the current state is identified, the desired maturity stage can be established. This will lead to a set of structural changes for the civil asset organization and the LE strategy. The LE strategy can be specified in detail after agreements are made about the planning of the structural changes for the civil asset organization. The framework can be used for other sites and disciplines after it is successfully implemented in the first case. The civil asset organizations located at the sites should eventually take the lead in using the framework.

In most of the cases the economic life of the civil structure turned out to be longer than planned. Therefore, it recommended for civil structures owned by oil companies to use a similar approach as for civil structures owned by public parties, having a longer functional life. The state of the civil asset organization should be brought to the 3rd stage of the framework, by applying successively implementing and supporting strategies during the civil structure’s lifespan. This implies that LE can be included in the daily (non-routine) maintenance practices.
7.3.2 Future research

Considering the context of the research, there are three directions for future research. These are in the directions of civil engineering, asset management and the oil and gas industry. Based on the insights gained during this research the opportunities for future research are defined.

**Research direction 1:** Civil engineering

Civil structures are of less vital importance than some of the other systems, such as rotating equipment and process elements. Therefore, there is a less urgent need to repair or replace components when the first signs of degradation are visible. However, civil aspects are often decisive for the scope of work when considering the quantities of material used for construction. Therefore it should be investigated what the best moment is to execute a LE from the civil engineering perspective. A possible research question is:

*What is the best moment to execute a lifetime extension of civil structures?*

The required input for this study is detailed statistics on the performance of the asset and cost estimates. Aspects to take into account are reliability, availability and maintainability (RAM) criteria. The result could provide insights into cost beneficial planning strategies.

**Research direction 2:** Engineering asset management

Not all assets are the same. Some assets provide fewer benefits for the company in monetary term, but could have a more social or political value. More insights should be gained in how to valuate assets when considering more aspects than only the financial costs and benefits. These insights could be used for portfolio management. A possible research question is:

*Which criteria should be considered when valuating assets?*

The approach to this research could be to use a survey. Methods such as the Q-methodology could be used to develop perspectives on different situations. These perspective, combined with the set of criteria could be used to develop possible trade-offs to be made.

**Research direction 3:** Oil and gas industry

For the oil and gas industry it is recommended to do a comparable study for the downstream business (refineries). Compared to upstream business there is much more pressure on budgets in the downstream business. This results in a different approach on how these assets are managed. A possible research question for this study is:

*What are the effects of budget limitations in maintenance decision-making?*

The required inputs for this study are insights from decision makers (plant managers) in the downstream and upstream business. A comparable study can be done to find out how trade-offs are made in maintenance decision-making.
8. LITERATURE


Shell. (2012b). Nigeria LNG FAIR+MS for Civil Instrumented Protected Functions and Pressure Equipment Integrity.

Shell. (2013). Nigeria LNG - Civil Asset Master Plan


Shell. (2014b). Civil RCM implementation in Nigeria LNG.


Appendix A. QUESTIONNAIRE DESIGN

In this appendix, the questionnaire design is discussed. First, a general overview of the process is provided. Second, the e-mails sent to the respondents is provided. Third, the questions asked to the respondents are shown.

I. Questionnaire process

Sample characteristics
The sample consists of respondents from the entire Civil Engineering skill pool of Shell Global Solutions. The respondents are from the regions Americas, EMEA and East, which means that there is a global variety of working locations. For this research there is less necessity for a random sampling, because all respondents are considered to be a civil expert to a certain degree. However, the reliability of the results would be increased when there is sufficient geographic variety of respondents, so that not all knowledge comes from one region.

Questionnaire protocol
After the first questionnaire design is made a feasibility check is done to estimate the duration of the questionnaire and to find out whether the results are the desired outcomes. A test group of 10 persons is used for the feasibility check. Their recommendations are used to finalize the questionnaire.

The questionnaire is divided in four categories, which are:
1. Personal information; information about the experiences of the respondent,
2. Case; external causes of failure and considerations made during the lifespan of an asset the respondent has the most knowledge about,
3. Lifetime extension projects; focus on successful lifetime extension project in which the respondent was involved, but also less successful projects and
4. Maintenance and inspection; The respondent's insights into the effectiveness of maintenance and inspections in practice.

The questionnaire contains three types of questions, (1) multiple choice questions focusing on experiences during the lifetime of the asset, (2) multiple choice questions to gain insights or opinions about certain phenomena and (3) short answer questions to underpin the answers provided by the multiple choice questions. Figure A-1 shows the structure of the questionnaire.
The structure of the questionnaire could be seen as a hierarchical one; the more knowledge the respondent has about a subject, the more questions are answered. This results in that some questions cannot be answered by a respondent if he or she does not have enough expertise in that certain subject. This way the answers provided will be the most realistic ones.

For some questions, such as how the respondent thinks about the current maintenance practices, an opinion is asked through a rating scale. For these kind of questions a six-point scale, thus without a center, is used. This means that the respondent cannot choose for the neutral option and is forced to give a positive or negative answer to the question. In case the respondent really does not have an opinion, he or she can choose for the option 'I don’t know'.

After two weeks an evaluation is done to find out whether there was a sufficient amount of respondents and what kind of information is missing in order to have sufficient background information for the interviews.
II. Communication

E-mail: Introduction
Dear colleague,

This e-mail was sent to you because you are considered to have knowledge in the field of civil engineering.

For my master thesis project I am doing a research in life extension strategies for civil structures. Historical cases point out that some life extension projects were successful and others were less successful. Time to find out why that happened! Besides the effectiveness of life extension projects, assets are also influenced by several factors from the context. As an input for my study I want to make an overview of these external factors to find out whether some aspect should be taken into consideration within decision-making processes.

You can help!
Because you have more experience in real life projects than I have, you can share your knowledge. The link below leads you to a short questionnaire, which will take about 10 minutes to fill in.

[link]

Thank you in advance for your help!
Your input will be used to make a decision-making model which can be helpful when considering a life extension project. The information will be processed anonymously and will be used for Shell purposes.

If you have any further questions about the questionnaire, my research project, tips and tricks, or other remarks, you can reply to this e-mail.

Kind regards,

Nicole Mooibroek
Graduate Intern - Asset Integrity Management
Shell Projects and Technology - Projects & Engineering Services
Shell Global Solutions International BV
III. Questionnaire

Dear colleague,

Your thoughts and experiences with (maintenance) projects are the most important input for this questionnaire. Take your time to answer the questions as good as possible. It will only take 10 minutes of your time.

Thank you for your help!

Personal information

1. At which region do you work at the moment?

<table>
<thead>
<tr>
<th>Region</th>
<th>Countries in Northern and Southern America, Canada etcetera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Americas</td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>Countries in Asia, the Pacific etcetera</td>
</tr>
<tr>
<td>EMEA</td>
<td>Countries in Europe and Africa etcetera</td>
</tr>
<tr>
<td>Other</td>
<td>Interpretation of respondent of other location</td>
</tr>
</tbody>
</table>

2. What is your main area of knowledge?

<table>
<thead>
<tr>
<th>Area</th>
<th>Specialization within the civil engineering department of Shell.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asset Maintenance &amp; Integrity</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Civil Infrastructure</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Civil Systems</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Site Planning</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Site Infrastructure</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Marine Facilities &amp; Coastal Engineering</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Ship-Shore Interface &amp; Transfer Equipment</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Geotechnical Design</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Refrigerated Storage Tanks</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
<tr>
<td>Engineering Business Improvement</td>
<td>Specialization within the civil engineering department of Shell.</td>
</tr>
</tbody>
</table>

3. How many years of work experience do you have in the oil and gas industry?

<table>
<thead>
<tr>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 2 years</td>
</tr>
<tr>
<td>2 to 4 years</td>
</tr>
<tr>
<td>5 to 7 years</td>
</tr>
<tr>
<td>8 to 10 years</td>
</tr>
<tr>
<td>More than 10 years</td>
</tr>
</tbody>
</table>
Definition of the case
The specific research is based on Nigeria LNG, Brunei LNG, Malaysia LNG and Bacton Gas Terminal, so information about these cases is preferred. If you were not involved with any of these assets, there is no problem, just fill in the name of another asset you have the most knowledge about.

4. Which of the following assets do you have the most knowledge about?

<table>
<thead>
<tr>
<th>Option</th>
<th>Field code [pipe:7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I don’t have knowledge about a specific asset</td>
<td>Respondent is redirected to question 33 and will not have any further questions about a case.</td>
</tr>
<tr>
<td>Bacton Gas Terminal</td>
<td></td>
</tr>
<tr>
<td>Brunei LNG</td>
<td></td>
</tr>
<tr>
<td>Malaysia LNG</td>
<td></td>
</tr>
<tr>
<td>Nigeria LNG</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Field code [pipe:7]. Name of another asset the respondent has knowledge about.</td>
</tr>
</tbody>
</table>

External causes of failure

5. What were the most important external causes of functional failures during the lifespan of [pipe:7]? (max. 6 options)

<table>
<thead>
<tr>
<th>Cause</th>
<th>Field code [external influences 1-6]. Sub-aspect of category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidents</td>
<td>‘Accidents’</td>
</tr>
<tr>
<td>Air pollution</td>
<td>‘Environmental effects’</td>
</tr>
<tr>
<td>Construction inadequacy</td>
<td>‘Asset-specific influences’</td>
</tr>
<tr>
<td>Design inadequacy</td>
<td>‘Asset-specific influences’</td>
</tr>
<tr>
<td>Earth quake</td>
<td>‘Environmental effects’</td>
</tr>
<tr>
<td>Effects of processing gas</td>
<td>‘Process-specific influences’</td>
</tr>
<tr>
<td>Effects of processing oil</td>
<td>‘Process-specific influences’</td>
</tr>
<tr>
<td>Exposure to chemicals</td>
<td>‘Process-specific influences’</td>
</tr>
<tr>
<td>High temperature</td>
<td>‘Environmental effects’</td>
</tr>
<tr>
<td>Ice</td>
<td>‘Environmental effects’</td>
</tr>
<tr>
<td>Low temperature</td>
<td>‘Environmental effects’</td>
</tr>
<tr>
<td>Manufacture inadequacy</td>
<td>‘Asset-specific influences’</td>
</tr>
<tr>
<td>Rain</td>
<td>‘Environmental effects’</td>
</tr>
<tr>
<td>Sabotage</td>
<td>‘Deliberate damage’</td>
</tr>
<tr>
<td>Soil quality</td>
<td>‘Environmental effects’</td>
</tr>
<tr>
<td>Terrorism</td>
<td>‘Deliberate damage’</td>
</tr>
<tr>
<td>Vandalism</td>
<td></td>
</tr>
<tr>
<td>Field of Influence</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Volcano</td>
<td>Field code [external influences 1-6]. Sub-aspect of category ‘Environmental effects’</td>
</tr>
<tr>
<td>Water</td>
<td>Field code [external influences 1-6]. Sub-aspect of category ‘Environmental effects’</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Field code [external influences 1-6]. Sub-aspect of category ‘Environmental effects’</td>
</tr>
<tr>
<td>Other</td>
<td>Field code [external influences 1-6].</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. Counting from start date the [pipe:7] came in operation, after how long did these influences occur? <em>(Estimate in Years)</em></th>
<th>7. How many times did the external influence cause a failure during the given time span?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 5 years</td>
<td>Less than 2 times</td>
</tr>
<tr>
<td>5 to 8 years</td>
<td>2 to 4 times</td>
</tr>
<tr>
<td>9 to 12 years</td>
<td>5 to 7 times</td>
</tr>
<tr>
<td>13 to 16 years</td>
<td>8 to 10 times</td>
</tr>
<tr>
<td>17 to 20 years</td>
<td>More than 10 times</td>
</tr>
<tr>
<td>More than 20 years</td>
<td>I don’t know</td>
</tr>
<tr>
<td>Reoccurring during the entire lifespan</td>
<td>I don’t know</td>
</tr>
<tr>
<td>I don’t know</td>
<td>I don’t know</td>
</tr>
</tbody>
</table>

Considerations during the lifespan of the asset

<table>
<thead>
<tr>
<th>8. What were the most important external influences on decision-making during the lifespan of [pipe:7]? <em>(max. 6 options)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in policies</td>
</tr>
<tr>
<td>Change of norms or standards</td>
</tr>
<tr>
<td>Local societies</td>
</tr>
<tr>
<td>Local species</td>
</tr>
<tr>
<td>Politics</td>
</tr>
<tr>
<td>Competition in the market</td>
</tr>
<tr>
<td>Change of capacity</td>
</tr>
<tr>
<td>Change of demands</td>
</tr>
<tr>
<td>Insufficient expertise at location</td>
</tr>
<tr>
<td>Ownership operated assets</td>
</tr>
<tr>
<td>Lack of involvement in maintenance plans</td>
</tr>
<tr>
<td>Insufficient priorities</td>
</tr>
</tbody>
</table>
Return on investment | Field code [considerations 1-6]. Sub-aspect of category 'Costs'
New technological developments | Field code [considerations 1-6]. Sub-aspect of category 'Technological change'
Life cycle costs | Field code [considerations 1-6]. Sub-aspect of category 'Costs'
Total cost of ownership | Field code [considerations 1-6]. Sub-aspect of category 'Costs'
Other | Field code [considerations 1-6].

9. Counting from start date of initiation, after how long did these influences occur? (Estimate in Years)

<table>
<thead>
<tr>
<th>Length of Influence</th>
<th>Yes</th>
<th>5 to 8 years</th>
<th>9 to 12 years</th>
<th>13 to 16 years</th>
<th>17 to 20 years</th>
<th>More than 20 years</th>
<th>Reoccurring during the entire lifespan</th>
<th>I don’t know</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 5 years</td>
<td>Yes</td>
<td>No</td>
<td>I don’t know</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 to 8 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 to 12 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 to 16 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 to 20 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than 20 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reoccurring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

10. Were the changes taken into consideration before the external influences occurred?

<table>
<thead>
<tr>
<th>Length of Influence</th>
<th>Yes</th>
<th>5 to 8 years</th>
<th>9 to 12 years</th>
<th>13 to 16 years</th>
<th>17 to 20 years</th>
<th>More than 20 years</th>
<th>Reoccurring during the entire lifespan</th>
<th>I don’t know</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 5 years</td>
<td>Yes</td>
<td>No</td>
<td>I don’t know</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 to 8 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 to 12 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 to 16 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 to 20 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than 20 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reoccurring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

11. For each of the following options, please indicate on a scale from 1 to 6 (1 = totally not important and 6 = extremely important) how important the change was in relation the performance of the asset during the total lifespan.

Field codes [considerations 1-6] Forced choice, which means that there is no neutral option (but there is an 'I don’t know' option, to give an indication from 1 to 6 on how important the changes were in the point of view of the respondent.

Lifetime extension projects
An important aspect is the lessons learned during lifetime extension projects. The questions below focus on the do’s and don’ts for these kind of projects. If you wish to share more of your experiences, please contact me at [e-mail].

12. Were you ever involved in a successful lifetime extension project?

Yes | Continue to question 14.
No  | Continue to question 13.

13. Were you ever involved in a lifetime extension project that was not successful?

Yes | Continue to question 19.
No  | Respondent is redirected to question 24.

14. For which asset was this project done?

<table>
<thead>
<tr>
<th>Asset</th>
<th>Field code [pipe:7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacton Gas Terminal</td>
<td>Field code [pipe:7]</td>
</tr>
<tr>
<td>Brunei LNG</td>
<td>Field code [pipe:7]</td>
</tr>
<tr>
<td>Malaysia LNG</td>
<td>Field code [pipe:7]</td>
</tr>
<tr>
<td>Nigeria LNG</td>
<td>Field code [pipe:7]</td>
</tr>
<tr>
<td>Question</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>15. / 20. Why was this lifetime extension project successful / not successful? (max. 20 words)</td>
<td>Possibility for the respondent to give more background information on the project as input for the interviews.</td>
</tr>
<tr>
<td>16. / 21. Which unit of this plant was the lifetime extension applied to?</td>
<td>For example: Tank X, Liquefaction-unit X, Pipeline X.</td>
</tr>
<tr>
<td>17. / 22. Was there already done some maintenance to this unit before lifetime extension?</td>
<td>Yes, No, I don’t know</td>
</tr>
<tr>
<td>18. / 23. What was the remaining useful life (RUL) of this unit before lifetime extension? (Estimate in Years)</td>
<td>Instruction: The RUL is the time until the system has reached its initial design life. For example, if a plant is designed for 20 years and operating for 15 years, the RUL is 5 years.</td>
</tr>
</tbody>
</table>
Effectiveness maintenance and inspections in practice

24. Apart from the case, please indicate on a scale from 1 to 6 (1 = worst and 6 = Excellent) to what extent the current maintenance practices improve system performance.

1 - 2 - 3 - 4 - 5 - 6 – I don’t know  
Instruction: Evaluate on the maintenance tasks deriving from the application of Reliability Centered Maintenance, or the effectiveness of maintenance tasks.

25. Why?

26. Apart from the case, please indicate on a scale from 1 to 6 (1 = worst and 6 = Excellent) to what extent the current inspection practices provide a sufficient quality of information to make well-considered decisions.

1 - 2 - 3 - 4 - 5 - 6 – I don’t know  
Instruction: Evaluate on the execution of Risk Based Inspections and aspects like condition-based, age-based and time-based inspections.

27. Why?

Results

37. Would you like to be informed about the final result of this research?

Yes  
Option to fill in an e-mail

No

38. Can I contact you to schedule an interview for more detailed information when relevant?

Yes  
Option to fill in an e-mail

No

Thank you for your contribution!
The results will be useful to gain insight into the opportunities for lifetime extension projects in the future and will be used for Shell purposes.
Appendix B. Detailed Questionnaire Results

In this section, more detailed information about the response for the questionnaire are provided. First, the background information on the sample is provided. After that, a statistic overview of all the responses are provided.

I. Background information on sample

The respondents were able to fill in the location at where they are currently working. The following locations were provided:

- Africa/middle east: All countries in Africa and the Middle East
- All: the respondent was pending between locations during the year
- Americas: North and South America
- East: Russia, Asia and Australia
- Europe: All countries in Europe
- Other: No location was provided.

An overview of the answers is shown in Figure B-1.

Figure B-1 shows that most of the respondents were located in Europe (41%), but the other areas were also sufficiently represented. Therefore, it can be argued the sample is a world wide representation of the civil engineering discipline.

After that, the respondents were asked about the years of work experience they had. In this research someone is considered to be an expert in case he or she has more than 10 years of work experience in the industry. An overview is shown in Figure B-2.
Figure B-2 shows that the majority of the sample (59%) has more than 10 years of work experience in the industry. Furthermore, the part of the sample having less than years of work experience is only 16%. Therefore, it can be argued the sample has sufficient experience in the industry.

Within the civil engineering discipline in Shell, there are different kinds of expertise. A variation of the different expertises would provide a wide range of knowledge. In case that different expertises experience similar problems, it would be more reliable to assume that the problem needs to be taken into account. An overview is shown in Figure B-3.

Figure B-3 shows that all expertise are covered by the respondents. A large part of the sample is covered by the expertises Civil Infrastructure (32%), Site Planning (21%) and Asset Maintenance & Integrity (14%). This can be explained by the assumption that these disciplines are mostly involved in LEs and therefore mostly triggered by the questionnaire. Each respondent got the possibility to choose for an asset they were, in their point of view, the most knowledgeable of. This will increase the accuracy of the answers they provided. An overview of the assets is provided in Figure B-4.
Figure B-4 shows that there were 23 cases used as input for the questionnaire responses. This confirms the worldwide representation of the civil engineering disciplines. Furthermore, it provided the opportunity to compare location specific aspects.
II. Responses for the influences from the context on system performance

The different influence from the context were subdivided in smaller, more tangible factors. The sum of factors was calculated as the total response for a type of influences. Table B-1 shows the responses for the influences on system performance.

### Table B-1: Response for influences on system performance

<table>
<thead>
<tr>
<th>Category</th>
<th>Factor</th>
<th>Response</th>
<th>Total category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accidents</strong></td>
<td>Accidents</td>
<td>4.60%</td>
<td>4.60%</td>
</tr>
<tr>
<td><strong>Deliberate damage</strong></td>
<td>Sabotage</td>
<td>2.87%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Terrorism</td>
<td>1.72%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vandalism</td>
<td>2.87%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>7.47%</strong></td>
</tr>
<tr>
<td><strong>Design and construction errors</strong></td>
<td>Construction inadequacy</td>
<td>13.79%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Design inadequacy</td>
<td>14.94%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manufacture inadequacy</td>
<td>3.45%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>32.18%</strong></td>
</tr>
<tr>
<td><strong>Environmental effects</strong></td>
<td>Air pollution</td>
<td>1.15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Earth quake</td>
<td>1.15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rain</td>
<td>8.62%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil quality</td>
<td>6.32%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volcano</td>
<td>0.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>12.07%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind speed</td>
<td>2.30%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>31.61%</strong></td>
</tr>
<tr>
<td><strong>Lack of maintenance</strong></td>
<td>Lack of maintenance</td>
<td>9.20%</td>
<td><strong>9.20%</strong></td>
</tr>
<tr>
<td><strong>Process-specific effects</strong></td>
<td>Effects of processing gas</td>
<td>4.02%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Effects of processing oil</td>
<td>1.72%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exposure to chemicals</td>
<td>5.17%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High temperatures</td>
<td>2.87%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ice</td>
<td>1.15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low temperatures</td>
<td>0.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>14.94%</strong></td>
</tr>
<tr>
<td><strong>N=174</strong></td>
<td></td>
<td></td>
<td><strong>100.00%</strong></td>
</tr>
</tbody>
</table>

Table B-1 shows that the decisive influences are environmental effects (31.6%), design and construction errors (32.2%) and process specific effect (14.9%). Therefore, these will be taken into account for this research.

The respondents also had the possibility to choose for another factor. These were divided over the different types of influences afterwards. Table B-2 shows the replacement of these factors.
### III. Maintenance success drivers

The respondents were asked what, in their point of view, the success drivers were for repair and maintenance practices. Their descriptions were placed into categories. These are shown in Table B-3.

<table>
<thead>
<tr>
<th>Driver</th>
<th>Description</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>Procedures</td>
<td>Flexible management system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Good system in place to capture the actions and actually execute them</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Well organized program to remove corrosion and repaint the offshore platforms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Prevents unplanned failures</td>
</tr>
<tr>
<td></td>
<td>Early identification</td>
<td>Defects are identified early and actions are taken to prevent total system collapse</td>
</tr>
<tr>
<td></td>
<td>New technologies</td>
<td>New technologies help to increase effectiveness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• New chemical treatments available in the market</td>
</tr>
<tr>
<td>Failure</td>
<td>Procedures</td>
<td>Not focused on improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Maintenance concepts are vague and open for interpretation</td>
</tr>
<tr>
<td></td>
<td>Resources</td>
<td>Funding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spares</td>
</tr>
<tr>
<td></td>
<td>Priorities</td>
<td>Reactive maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Situations beyond repair</td>
</tr>
<tr>
<td></td>
<td>Organizational change</td>
<td>Lacking continuity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Change of people involved</td>
</tr>
<tr>
<td>Total (N=23)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IV. Responses for the influences from the context on the decision-making process

The different influence from the context were subdivided in smaller, more tangible factors. The sum of factors was calculated as the total response for a type of influences. Table B-4 shows the responses for the influences on decision-making.

<table>
<thead>
<tr>
<th>Category</th>
<th>Factors</th>
<th>Response</th>
<th>Total category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Costs</strong></td>
<td>Return on investment</td>
<td>5.13%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Life cycle costs</td>
<td>9.62%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total cost of ownership</td>
<td>6.41%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shutdowns</td>
<td>3.85%</td>
<td><strong>25.00%</strong></td>
</tr>
<tr>
<td><strong>Demand / Supply</strong></td>
<td>Competition in the market</td>
<td>3.85%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change of capacity</td>
<td>4.49%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change of demands</td>
<td>4.49%</td>
<td><strong>12.82%</strong></td>
</tr>
<tr>
<td><strong>Knowledge</strong></td>
<td>Insufficient expertise at location</td>
<td>7.05%</td>
<td></td>
</tr>
<tr>
<td><strong>Local aspects</strong></td>
<td>Local societies</td>
<td>3.21%</td>
<td><strong>3.85%</strong></td>
</tr>
<tr>
<td></td>
<td>Local species</td>
<td>0.64%</td>
<td></td>
</tr>
<tr>
<td><strong>Management</strong></td>
<td>Management operated assets</td>
<td>3.21%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lack of involvement in maintenance plans</td>
<td>12.18%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Insufficient priorities</td>
<td>11.54%</td>
<td><strong>26.92%</strong></td>
</tr>
<tr>
<td><strong>New technologies</strong></td>
<td>New technological developments</td>
<td>3.21%</td>
<td><strong>3.21%</strong></td>
</tr>
<tr>
<td><strong>Norms / Regulations</strong></td>
<td>Change in policies</td>
<td>6.41%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change of norms or standards</td>
<td>8.33%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Politics</td>
<td>6.41%</td>
<td><strong>21.15%</strong></td>
</tr>
<tr>
<td><strong>N=156</strong></td>
<td></td>
<td>100.00%</td>
<td><strong>100.00%</strong></td>
</tr>
</tbody>
</table>

Table B-4 shows that the decisive influences are costs (25%), management (26.9%) and norms/regulations (14.9%). Therefore, these will be taken into account for this research.
V. Inspection success drivers

The respondents were asked what, in their point of view, the success drivers were for inspections. Their descriptions were placed into categories. These are shown in Table B-5.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Success</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Amount of data</strong></td>
<td>Sufficient (general) data/information for decision-making</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>Helps to plan your work and monitor condition status</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shows the integrity of the system</td>
<td></td>
</tr>
<tr>
<td><strong>Tools</strong></td>
<td>Enough tools for a dedicated personnel to carry out detailed inspection and highlight areas of improvement</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Balanced with costs and risks</strong></td>
<td>Balanced between cost of inspection and risk of missing essential information</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Awareness</strong></td>
<td>Unless inspections are performed to define deficiencies then the site is unaware of issues</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Failure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Focus</strong></td>
<td>No plan, all about survival</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>Improvements needed on scope of work</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Civil inspection is often superficial</td>
<td></td>
</tr>
<tr>
<td><strong>Knowledge</strong></td>
<td>More information needed on concrete life</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>Significant faults are not detected by experts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expert interpretation needed and feedback to improve strategy</td>
<td></td>
</tr>
<tr>
<td><strong>Effort</strong></td>
<td>Insufficient effort</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Fireproofing removal is hardly done to check the condition of the main steel structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improvements needed in reporting of findings</td>
<td></td>
</tr>
<tr>
<td><strong>Priorities</strong></td>
<td>Civil was not included in inspection program</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>Minimum budget</td>
<td></td>
</tr>
<tr>
<td><strong>Inspectors</strong></td>
<td>Local contractors used for inspections</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Capacity organization</strong></td>
<td>Reduced capacity to timely execute the corrective measures</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Shell should be much more in control (of the asset)</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Total (N = 28)</strong></td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

As already shown in the literature, the respondents confirm that the factor ‘daya’ is a driver for successful decision making. Furthermore, the right focus and a lack of knowledge are known drivers for failures.
In this section the specific multiple-case study design is provided. First, more background information about LNG-plant is provided. After that, the data collection protocol, the emails sent to the interviewees, and the specific questions that were asked are discussed.

I. Background on LNG-plants

The scope of the LE for CASE 4 is recently identified through inspections. This scope basically consists of all aspects related to steel, concrete, insulation and painting. At the moment, an explorative study is done to extend the functional life of the plant with another 20 years. The CASE 4 plant consists of 6 trains of which the first one came in operation in 1999 and the last one in 2007. As shown in Figure C-1 these trains are the units of the plant in which the liquefaction process takes place. Here, the natural gas is cooled to a temperature of approximately -160°C at atmospheric pressure. These conditions ensure that the natural gas condenses to a liquid, so that it can be stored and shipped more easily and in a safer way.

![Figure C-1: Basic Block Diagram of a LNG Train, Adapted from Shell (2014)](image-url)
II. Data collection protocol

The case study process is for a large extent dependent on the results from the questionnaire. The following scenarios of the questionnaire results, and the corresponding actions, are defined:

1. Sufficient amount of data provided by questionnaire
   In case that the questionnaire provides a sufficient amount of data, the interviews will focus on the idea behind the answers provided by the questionnaire.

2. Insufficient number of respondents questionnaire (n<40)
   The response rate is estimated to be 15%. The questionnaire will be send to 274 respondents, which means that a number of 40 respondents would be sufficient. In case that there were an insufficient number of respondents of the questionnaire, the questions will also be asked to the interviewees.

3. Insufficient (case specific) information provided
   In case that there is insufficient information provided by the questionnaire, an analysis of missing data is made and translated into interview questions. Besides, supporting documentation is asked and the questions asked in the questionnaire will also be asked to the interviewees.

The case interviews will focus on the level 1 and 2 questions as defined by Yin (2009, p. 74). The categories of questions are (1) Personal information; information about the experiences of the respondent. (2) Case in general; evaluation of the total lifespan of the system and the considerations the interviewee had to make, (3) Perspective on lifetime extension; successful strategies based on the experiences of the interviewee, (4) Recommendations; recommendations for improvement from the interviewee.

The target group is based on the role or function and whether the interviewee was involved in the projects used for this research. In order to ensure validity of the information, three different perspectives on the case are used, which are decision maker, operations and engineering.

During the interviews evidence is collected through asking for specific examples supporting the answers. After that the answers are tested to be complete, relevant, clear and valid. The interview is also asked to fill in a hard-copy version of the questionnaire if he or she have not filled it in yet.

Within one week the interview outcomes are evaluated to find out which information is missing. The interview minutes, together with the remaining questions are sent to the interviewee for verification purposes.
The interview outcomes together with documentation about the case are used to make a case report, which explains the reason behind the functioning of each unit of analysis in practice. The technique of pattern matching is used to define the conclusion of the multiple-case study. This conclusion will lead to specific requirements for the decision-making model for CASE 4. An overview of above described process can be found in Figure C-2. 

![Figure C-2: Process of translating the outcomes from the multiple-case study into requirements for the LE of NLNG (Own Ill.)](image)
VI. Communication

Email: New respondent - Introduction
Dear [Name],

For my master thesis I am doing a research in life extension strategies for gas terminals and LNG plants. Basically I want to make an inventory of the external influences and lessons learned during LE projects as an input for a decision-making model. [reference] told me that you are [involvement in case], so hopefully you can give me some insights into what determines a successful life extension project.

Do you have a moment next week for a short discussion?

Thanks in advance for your help.

Kind regards,

Nicole Mooibroek
Graduate Intern - Asset Integrity Management
Shell Projects and Technology - Projects & Engineering Services
Shell Global Solutions International BV

Email: Respondent questionnaire – Introduction
Dear [Name],

Thank you for your useful input for the questionnaire about life extension projects. I saw that you have knowledge about [case]. Do you have a moment next week to tell me more about your experiences?

Thanks in advance for your help!

Kind regards,

Nicole Mooibroek
Graduate Intern - Asset Integrity Management
Shell Projects and Technology - Projects & Engineering Services
Shell Global Solutions International BV

Email: Follow up
Dear [Name],

First of all, thank you for the useful input during the interview. Within one week you can expect the interview report. Could you please give your approval or remarks to this report?

In response to the interview I have [number] remaining questions:
1. [Question]
2. [Question]
Kind regards,

Nicole Mooibroek
Graduate Intern - Asset Integrity Management
Shell Projects and Technology - Projects & Engineering Services
Shell Global Solutions International BV

Dear [Name],

The interview report can be found in the attachment. Could you please give your approval or remarks to this report?

Thank you for your help!

Kind regards,

Nicole Mooibroek
Graduate Intern - Asset Integrity Management
Shell Projects and Technology - Projects & Engineering Services
Shell Global Solutions International BV

VII. Interview questions

Introduction
Short description research, main goal, interview outline, roles during the interview (I ask the questions etc), how the interview data will be processed, what will be done with the results, duration of the interview, follow up (interview minutes).

Personal information
Name:
Function/Expertise:
Case:
Region/Location:
Work experience:
Case study: Performance during the total lifespan of the asset

1. **External causes of failure**
   The most important external causes of failure mentioned in the questionnaire were related to design and construction error and environmental effects.
   a. Considering these aspects, what were the main external causes of failure during the lifespan of [case]?
   b. Why did these failures occur?
   c. What kind of failure mechanism was applicable to this situation?
      (Option to make drawing of the situation)
   d. What were the effects?

2. **Interventions**
   The results of the questionnaire show that the current procedures are good enough, but that the priorities are set the wrong way and that there are often problems with resources and organizational change.
   a. Can you explain how these aspects affected the maintenance practices at [case]?
   b. What kind of maintenance strategy is used at the facility? (RCM based etc)
   c. What kind of (maintenance) interventions were taken during the lifespan?
   d. What determines the effectiveness of possible interventions taken during the lifespan?
   e. Why are these effective?

3. **Inspections**
   The results of the questionnaire show that there are a lot of difficulties regarding the inspections. Aspects mentioned were focus, priorities, effort, knowledge, inspectors used, and the capacity of the organization.
   a. Can you explain how these aspects affected the quality of inspection at [case]?
   b. How are the inspections done at the facility? (risk-based, age-based, condition-based etc)
   c. What determines the success of inspections?
   d. How can you explain this?

4. **Decision-making**
   What are the external factors influencing the decision-making process of the case? Focus on management, norms and standards and costs.
   a. What were the main considerations you had to make during the lifespan of the case?
   b. How was the decision-making process organized at [case]?
   c. Do you think this is effective?

5. **Lifetime extension**
   a. What are the possibilities for a lifetime extension for CASE 4?
   b. Which decision should be made for the LE?

6. **Recommendations**
   What are your further recommendations regarding LEs?
Appendix D. RECOMMENDED ACTIONS FROM MULTIPLE-CASE STUDY

In this appendix, the raw data of the recommendations as result of the multiple-case study is provided. The recommendations are provided by the interviewees. Each recommendation was coded and categorized into decision elements. For each decision element, the recommendations can be linked to a current state of the civil asset organization, as well as the LE.

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>Raw data</th>
<th>Decision element</th>
<th>Focus and priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Advice. The same designs are made both for assets with an economic life of 10 and 30 years. This could be improved by applying simpler design classes. Standardization is possible, but not easy.</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>1</td>
<td>One should have defined to scenario’s for the future before the decision to rejuvenate the plant.</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>1</td>
<td>The decision to extend the life of the plant is only made when the initial design life is finished. Advice. Therefore one should understand why the LE should be done.</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>1</td>
<td>Advice. Upgrading is not always the best option, one should question whether there is a sufficient amount of capacity.</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>2</td>
<td>Advice. The most effort needs to be put into the project during the engineering phase. Advice. It is recommended that, for a Brownfield project, more (detailed) engineering work is done prior to taking the Investment Decision. This is required to develop a more accurate cost estimate and prevent scope growth during the execution phase.</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>3</td>
<td>Advice. An expansion should not be considered in principle.</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>3</td>
<td>Advice. Maintenance approach; keep what you have got at a multistage level. Establish the minimum of what you should do; the basis should function at a 100% level.</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>4</td>
<td>Main problem for this cost overrun was that the contractor was a ‘greenfield’ contractor and was not experienced with brownfield projects. Everything that was damaged needed to be replaced in his point of view.</td>
<td>Contracting</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. Do not be distracted by possibilities to increase the production quantities etcetera</td>
<td>Focus and priorities</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td></td>
<td>Raw data</td>
<td>Decision element</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. One should understand that the core of rejuvenation is <strong>maintenance and not project management.</strong></td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Contractors experienced in NB projects can only think about ‘new’. This is also related to the difference between project management and LE.</td>
<td>Contracting</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Advice.</strong> Downscaling production quantities inherently means that the OPEX should decrease. This is done through the principle of de-complexing, which means that the LE project is also used to decrease the size of the plant.</td>
<td>Planning and costs, Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Advice.</strong> Main consideration should be that all <strong>things present at the site should be maintained as well.</strong></td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td><strong>Advice.</strong> Make a <strong>Cost/Benefit Analysis</strong>; what will be the expected lifespan of the plant and gas reserves.</td>
<td>Focus and priorities, Planning and costs</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>General idea is to trace everything that is damaged and to repair it (also heat exchangers etc).</td>
<td>Focus and priorities, Performance measurement</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>It might be more economically advantageous to just maintain the facility instead of performing a LE project.</td>
<td>Focus and priorities, daily maintenance</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>At CASE 1 a good specification was used, which resulted in sufficient quality of the concrete. The main difference between these two situations is the ability of the contractor to deliver the quality.</td>
<td>Contracting</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td><strong>Advice.</strong> More attention should be paid to <strong>supervising</strong>, It is Shell’s policy to use EPC contracts. This means that contractors execute their work and then leave the site. Shell is then fully responsible for the operational aspect. Innovative contracts (like DBFM contracts) could provide a solution for this.</td>
<td>Contracting</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Advice.</strong> The selection of contractors is really important. They are <strong>preferably specialized in maintenance projects</strong> or daily experience of “what type of maintenance is needed” is necessary.</td>
<td>Contracting</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>Advice.</strong> Better <strong>work packaging</strong> for contracts.</td>
<td>Contracting</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Need to continuously remind workers to comply with method of erection/dismantling of scaffold, use fit gloves, barricade work area and maximize the use of crane to lift material.</td>
<td>Contracting</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td><strong>Advice.</strong> The <strong>actual state of the site</strong> is important to take into consideration.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>The civil scope mainly includes thermal insulation, which means that the <strong>size of the plant is decisive for the costs.</strong></td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>An integrity issue that has received significantly more attention in recent years is material embrittlement by low temperatures (temperature cooling systems temperature -20°C). This is applicable for CASE 1 as well.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Advice.</strong> Improvements will be required in this area.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Advice.</strong> Norms/standards should be <strong>balanced with the minimum requirements.</strong></td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>Inter-</td>
<td>Raw data</td>
<td>Decision element</td>
<td></td>
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<tr>
<td>---</td>
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<td></td>
</tr>
<tr>
<td>viewee</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. A non-metal cladding system should be used instead of a metal cladding system. This was also done at CASE 2.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. More attention should be paid to <strong>working accurately</strong>. For steel 70% of the job consists of cleaning/blasting and 30% of the painting work itself.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. For a LE it is important to consider whether the <strong>proposed solution is acceptable and safe</strong>. One could make unnecessary calculations leading to the conclusion that the proposed solution is not possible in theory. This does not mean that it is not possible in practice.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. Be careful with the adoption of <strong>new norms and standards</strong>. These need to be used to <strong>establish the level of safety</strong> for the next contract period. It is important that the important changes in norms are not overlooked, such as the new norms for earth quakes (Kobe plant in Japan was the reason for establishing these norms). These kind of changes should be really taken into account.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>The focus should lie on the flare structures and the cooling water facilities. For the latter, the sources came from places in the middle of nowhere and there was a sufficient amount of water in these sources. However, during the last 20 years houses were built near this source, so it should be investigated whether it is possible to draw water from this source for the coming 20 years.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. Do not focus too much on the design. Everything is different in practice.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. More attention should be paid primary to the <strong>protection of the construction</strong> or, in other words, the quality. Climate conditions are of secondary order in these cases.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>LNG plants are mainly damaged through <strong>external corrosion and not process related aspects</strong>. This external corrosion can be limited by painting the unit. External corrosion is often not visible and is therefore secondary in order of priorities.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. Larger equipment (mechanical; electro motors, pumps) is often in good condition and could last for another round (20 years). Do not be tempted to replace these!</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. One should consider using galvanized steel or stainless steel for claddings.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. The connections between the units are the most difficult to work with. Take this in consideration in the scope definition.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. The scope of work of the LE is important. The main consideration should be <strong>how to find out what the scope of work actually</strong> is. 80% of the plant is isolated, so openings in the construction need to be made for inspection.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Advice. The critical circuits need to be identified. One of the critical circuits is, for example, rotating equipment.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Advice. For the construction the <strong>‘load-side’ and the ‘strength-side’ should be considered</strong>. For the load-side this means that insights should be gained into the different kinds of loads on the construction. For the strength-side it means that insights should be gained into the degradation mechanisms and the speed of degradation. Atmospheric corrosion could play a major role.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>Inter-</td>
<td>Raw data</td>
<td>Decision element</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>viewee</td>
<td>6</td>
<td>Advice. More <strong>inspections of critical points</strong> are needed before shutdown, so that during the shutdown proper maintenance could be carried out.</td>
<td>Focus and priorities</td>
</tr>
<tr>
<td>6</td>
<td>People should be aware that it <strong>all starts with the design</strong>.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td><strong>Advice. Safety factors could be reconsidered.</strong> Currently these factors are established in a deterministic way. A probabilistic approach could be considered.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>Advice.</strong> Relook into doing <strong>more wholesome rejuvenation work</strong> rather than only certain parts of equipment. e.g pump motor was replaced but pump was not even though it was in bad condition.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td><strong>Advice.</strong> The challenge is to define the scope of the life extension; this should be done in an intelligent way. Think, for example, about how much scaffolding and blasting is needed, these aspects have a lot of influence on the actual scope.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td><strong>Advice.</strong> Ensure to collect a sufficient amount of information to take the right decisions.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Advice.</strong> Perform quality assurance control on painting and insulation to define the state of the art. At the same time quantity surveying should be done to reassess what is actually the scope (square meters of painting etc.) These two aspects together can be used as input for the contracting strategy. The respondent emphasizes that this is not a project strategy!</td>
<td>Focus and priorities, Contracting</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td><strong>Advice.</strong> Key is to put <strong>sufficient effort</strong> into the inspections.</td>
<td>Focus and priorities, Performance measurement</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>After finding some spots of corrosion one could consider to strip the entire unit. However, it could differ per train whether or not there is corrosion!</td>
<td>Focus and priorities, Performance measurement</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Advice.</strong> Start with identifying what should be done and <strong>define the priorities by inspecting whether the units that should be isolated</strong> actually are isolated and whether it is ‘warm’ or ‘cold’ isolation.</td>
<td>Focus and priorities, Performance measurement</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>At <strong>CASE 2</strong> there are only limited climate influences, main bad actors are cooling towers. Investigate these and take the down pool area of these towers into account during maintenance. An inspection interval of 5-10 years is insufficient, because over there the corrosion rate is much higher than at the rest of the plant. These influences are bigger than influences from the sea for example.</td>
<td>Focus and priorities, available technology</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Advice.</strong> One should be critical when considering to <strong>change the design</strong> (for example the oil seals). Some aspects are not included in the current DEPs but are <strong>incorporated in the daily practices</strong>. Certain limitations could be covered by another methodology than the current DEPs prescribe, but are not limiting the actual performance of the system.</td>
<td>Focus and priorities, daily maintenance</td>
<td></td>
</tr>
<tr>
<td>Interviewee</td>
<td>Raw data</td>
<td>Decision element</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
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<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. Invest in stainless steel cladding (sort of external skin of the plant). Currently the cladding is made of aluminized steel and there is a lot of damage. In order to replace the cladding a lot of scaffolding is needed. One should realize that the labor costs and costs for scaffolding will vastly increase in the future. Therefore, replacing the cladding should be done on a short term.</td>
<td>Focus and priorities, Planning and costs</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. An inspection and monitoring plan should be included into the LE program. Advice. A statistic overview of the performance of the plant should be made to track the performance over the years.</td>
<td>Performance measurement</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. One could include sanctions into the reports, but the risks defined are really instinctive. It should be underpinned better whether there is an urgent need execute the plans and be clear about the consequences.</td>
<td>Performance measurement</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. One should show that they actually going to do something with the plans.</td>
<td>Performance measurement</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Advice. The RBI concept should be included into the maintenance programs from the start of operation, it is not possible to start with this concept when you are halfway there.</td>
<td>Performance measurement</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>At Sakhalin LNG external RBI is used to inspect the current state of isolation. Inspection windows are often used for these inspections, but these do not represent the current state of the rest of the unit. Exposure to atmospheric influences is higher at these windows due to opening en closing of these windows.</td>
<td>Performance measurement</td>
<td></td>
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<tr>
<td>5</td>
<td>Advice. External RBI is particularly useful for new technologies. During the LE project an inspection program should be made immediately to gain insight into the way the system functions. This should not be done for the entire plant, because it is too expensive.</td>
<td>Performance measurement</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. Inspections should be done by experienced people, preferably a combination of an engineer and someone involved in daily operations. They should constantly ask themselves whether they are critically enough.</td>
<td>Performance measurement, Team composition</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advice. It is better to perform a more extensive inspection during a regular shutdown and to repair these sections immediately. It costs more and takes more time to have limited inspections and then strip the entire train.</td>
<td>Performance measurement</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Advice. First step is to perform an inspection of high quality at the production facilities to assess what the critical aspects are.</td>
<td>Performance measurement, Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Advice. The steps are: a. Visual inspection to see whether there is already some condensation. b. Thermographic inspection for the point not visible during visual inspection. c. Involve people with reliability expertise to assess what should be done exactly.</td>
<td>Performance measurement, Team composition</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Advice. Avoid rework by tighten supervision and inspection e.g the installation of trays into absorber columns were done twice.</td>
<td>Performance measurement, contracting</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Advice. At the smaller locations, such as CASE 1, there less engineers present. The solution could be to go to the site more often.</td>
<td>Workforce, Team composition</td>
<td></td>
</tr>
<tr>
<td>Inter-viewee</td>
<td>Raw data</td>
<td>Decision element</td>
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<td>4</td>
<td><strong>Advice.</strong> Experience from practice should be more included in the development program of a civil engineer. A civil engineer should have more knowledge about the process (temperatures etc.).</td>
<td>Workforce</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td><strong>Advice.</strong> Shell could have a lessons learned database, but what about the engineering contractors? They are the ones executing the project and make the same mistakes all over again. A solution can be found in an industry wide database of lessons learned.</td>
<td>Vertical integration</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td><strong>Advice.</strong> People should know the best practices and repeat lessons learned during earlier experiences.</td>
<td>Workforce</td>
<td></td>
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<tr>
<td>4</td>
<td><strong>Advice.</strong> More proactive plans are needed** (probabilistic methods); RCM is already based on proactive plans.</td>
<td>Performance measurement, Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Because engineers have no insights into the daily operations at the site it is hard to ‘do the right things’. Therefore these engineers need to go to the sites and work together with people in daily operations.</td>
<td>Workforce, Team composition</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td><strong>Advice.</strong> You should have interviews with people who have been at the site location to find out what the changes were during the last years regarding the daily operations, behaviors etc.</td>
<td>Workforce, Team composition</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td><strong>Advice.</strong> The LE-program should be adjusted to the regular maintenance program. This should be a long term planning for maintenance.</td>
<td>Daily maintenance</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Advice.</strong> Do not include the scheduled maintenance practices into the LE project. These are not a part of LE and important to be performed well.</td>
<td>Daily maintenance</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Starting point for current design practices is to design for operation and safety.</td>
<td>Daily maintenance</td>
<td></td>
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<tr>
<td>5</td>
<td><strong>Advice.</strong> The use of a 3D model during design phase could provide insights into the maintainability of the plant.</td>
<td>Daily maintenance</td>
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</tr>
<tr>
<td>5</td>
<td><strong>Advice.</strong> The best way to deal with this gap is to involve people experiences in the daily operation and maintenance practice.</td>
<td>Daily maintenance, Team composition</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Advice.</strong> People in daily operations are actually really good in assessing the current state and they should establish the scope for LE and small maintenance.</td>
<td>Daily maintenance, Team composition, Performance measurement</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td><strong>Advice.</strong> The project should be fit for purpose. One should think in what is already present at the site.</td>
<td>Focus and priorities</td>
<td></td>
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<tr>
<td>6</td>
<td>The cryogenic insulation needs to have a certain level of performance. When this performance level is lower than required condensation could occur. This could eventually result in growth of algae if not intervened at early stage.</td>
<td>Focus and priorities</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td><strong>The economic impact,</strong> which indirectly means the size of the plant, is decisive for the online/offline ratio.</td>
<td>Planning and costs</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Also routine could be dangerous in case of online rejuvenation (accidents etc.).</td>
<td>Planning and costs</td>
<td></td>
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</table>
Double-block and bleed valves are used for safety requirements. However, these were not placed in the initial LNG factories. Online replacement of these valves could be rather dangerous. Therefore it should be considered whether there is an urgent need to replace these valves.

It is difficult to execute a LE online, because of the ‘cold isolation’ (inner side). This is much easier to do at refineries, because of ‘warm isolation’ (outer side). In that case, there is a slight loss of production quantities due to heat loss.

There are also difficulties with scaffolding in case of an online LE. The scaffolding then needs to be placed online, which will cause a major loss of efficiency.

There is a sufficient amount of budget available for maintenance at LNG plants and often most of this budget is not spent. This is mainly due to the fact that some of the tasks need to be performed in an offline mode, which means that there is temporary no LNG production.

Advice. This should be balanced with the marketing department.

Advice. Inspection of piping need to finish within one month to allow sufficient time for preparation of test packs.

Advice. Minimized shutdown work. Maximized on-stream work for painting.

Advice. Some materials arrived late. All materials need to be available before shutdown. A delay of one discipline will also delay others.

Advice. The shutdown duration is not sufficient to complete the painting and blasting scope. On-stream work need to be maximized.

Advice. Utilize your shutdown windows and find the optimal ratio between online and offline work, a minimum amount of work should be done in the shutdowns.

Red lead based paint removal work prevent other disciplines to work in the same area. Detail planning need to be in place and again carry out on-stream work as much as possible to minimize interference.

If spare parts are not sold anymore a solution should be found before obsolescence takes place. At CASE 4 there is a lot of obsolescence at the moment. One should negotiate with the vendor about the spare parts before LE. The respondent indicates that the vendor only wants to sell new spares and probably put a new type of these spares to the market.

Advice. Here (in Rijswijk) the plans are made at high level, but one should go to the site. Ideally, the team consists of locals and expats. This way experience from practice and good insulation/painting inspectors are at the site.

Advice. The LE plans should be discussed as a team, which means that interaction is needed with other disciplines (mechanical and rotating). This should be done at the site, one should have a hands-on approach.

Advice. The link between the LE project and O&M should be created from day 1. It is important that these people are involved and dedicated into the team. Most of the time contractors are used, but these companies do not know the plant like people in O&M do.
The project comprises of people from different culture and nations. It is very challenging to bring everybody together.

**Advice.** Attention should be paid to the organizational aspects, like composition of team and the selection of contractors, so that the focus on knowledge and skills can be improved. At CASE 2 people had to do a **skill test** before working at the site. At CASE 4 everything is locally organized.

**Advice.** Discipline engineers (civil engineer etc) should be more involved in **maintenance and inspection works** in the operational phase of the project.

**Advice.** Inspections are done by mechanical engineers, but should also include civil engineers.

**Advice.** Engineers should definitely be involved, also for dealing with the degradation mechanism.

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>Raw data</th>
<th>Decision element</th>
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<tbody>
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<td>Team composition</td>
</tr>
<tr>
<td>4</td>
<td><strong>Advice.</strong></td>
<td>Team composition, Contracting, Workforce</td>
</tr>
<tr>
<td>2</td>
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<td>Team composition, Focus and priorities</td>
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<td>4</td>
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<td>Team compositions, Performance measurement</td>
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Appendix X. CASE REPORTS

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Confidential