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LIFE CYCLE MANAGEMENT OF TVO NUCLEAR POWER PLANT

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Supervisor: M.Sc. Antti Raukola

TIIVISTELMÄ

Lappeenranta University of Technology
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TVO:n ydinvoimalaitoksen elinkaarihallinta

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Tämä diplomityö tutkii eri elinkaarihallinnan menetelmiä ja vertaa niitä TVO:n menetelmiin. Lisäksi TVO:n prosessin ongelmakohdat tunnistetaan ja niihin esitetään ratkaisuja. Vertailukohteina toimii ydinvoimateollisuuden lisäksi vesivoima, fossiiliset voimalaitokset sekä paperiteollisuus.

Sähkön hinnan jatkaessa laskuaan on elinkaariajattelusta tullut ajankohtaista myös ydinvoimayhtiöille. Ydinvoimalaitoksien pitkän suunnitellun käyttöiän ansiosta laitoksen elinkaaren aikana voi tapahtua useita asioita, jotka vaikuttavat laitoksen investointitarpeisiin. Turvallisen sähköntuotannon varmistamiseksi eri laitososia on joko muokattava tai uusittava.

Elinkaariajatteluun kuuluu tehokas laitoksen kunnon valvonta, laitoksen ikääntymiseen vaikuttavien ilmiöiden tunnistaminen, sekä ikääntymistä hillitsevien toimenpiteiden pitkän tähtäimen suunnittelu. Hyvällä ennakkosuunnittelulla pyritään varmistamaan se, että laitoksella voidaan tuottaa sähköä koko sen jäljellä olevan käyttöiän aikana. Kun tarpeiden tunnistus ja suunnittelu tehdään hyvissä ajoin mahdollistetaan myös investointien optimointi. Paras hyöty pyritään saamaan ajoittamalla oikeat investoinnit oikeaan aikaan.

ABSTRACT

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Life Cycle Management of TVO Nuclear Power Plant

Master's Thesis

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99 pages, 33 figures, 8 tables, and 4 appendices.

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Keywords: Life Cycle Management, Ageing Management, Nuclear Power, Investment Planning.

This thesis explores different life cycle management techniques and compares them to the ones used at TVO. Problems with the TVO process are identified and different solutions are presented. In addition to the nuclear industry, benchmarking is done with representatives of hydropower, fossil fired power, and the paper industry.

A life cycle approach to nuclear power maintenance and modification investments has become increasingly lucrative for utilities as electricity prices continue to drop. As nuclear power plants tend to have long design life times, there are several things that can happen during this time that contribute to the need to modify or upgrade plant systems, structures, or components.

An effective way of monitoring plant condition, identifying phenomena that contribute to plant ageing, and having plans for mitigating actions are examples of life cycle thinking. Actions that are necessary for the continued operation of the plant for its remaining life time are identified and planned long in advance. Enough time to plan also makes it possible to find the optimal time to implement these actions, thus maximizing the return on investment.

FOREWORD

This thesis was written as a conclusion to my Master's studies in Lappeenranta University of Technology. It was commissioned by UPM Kymmene Oyj, in co-operation with Teollisuuden Voima Oyj.

First of all I would like to thank both UPM and TVO for giving me the opportunity to research this interesting subject. Special thanks to my supervisor Antti Raukola, who has diligently guided me toward this finished product, my examiner Juhani Hyvärinen, who has provided sage advice and ideas on the subject matter, and to Timo Palomäki and Matti Vaaheranta at TVO for providing direction and all the information I needed to form a picture of TVO's process.

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A final thanks to my friends and family for their support during my studies, and to my girlfriend Soili for proofreading and support on the home front.

Tampere, July 18th 2016

Joel Maunula

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TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AMP	Ageing Management Program
CDF	Core Damage Frequency
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
LCM	Life Cycle Management
LTP	Long Term Plan
NPP	Nuclear Power Plant
NPV	Net Present Value
NRC	Nuclear Regulatory Commission (United States)
O&M	Operation and Maintenance
PAM	Proactive Asset Management
PLIM	Plant Life Management
POMS	Proactive Obsolescence Management System
PRA	Probabilistic Risk Assessment
RCM	Reliability Centered Maintenance
SSCs	Systems, Structures, and Components
STUK	Nuclear and Radiation Safety Authority (Finland)
T&M	Testing and Maintenance
TVO	Teollisuuden Voima Oyj

1 INTRODUCTION

The purpose of this thesis is to provide insight into plant life cycle management (LCM) at nuclear facilities, with emphasis on the methods used by Olkiluoto power utility Teollisuuden Voima Oyj (TVO). The TVO methods will be benchmarked against other methods used or recommended by regulators, power utilities and industry. The thesis will also help TVO shareholders to understand the investments associated with life cycle management of a nuclear facility, how they are prioritized, and what to expect from the near future.

Nuclear power plants (NPPs) tend to have fairly long design life times. Design life time is an operating time for which the plant supplier guarantees that the plant stays within a safe design envelope, as long as it is maintained according to supplier recommendations. Older reactors were designed to operate for 25-30 years, while somewhat newer models such as the Olkiluoto reactors were designed for 40 years of operation. Operating license periods vary by country, for example in the United States the NPPs were immediately granted operating licenses for their entire design lifetime, while in Finland operating licenses were granted for shorter, fixed time periods. Initially, Finnish operating licenses were granted for 5-10 years, later on for 20 years at a time. A condition for a longer operating license was that license conditions needed to be reviewed every 10 years. (United States Nuclear Regulatory Commission, 2015; TVO 2009, 5-8; STUK 2002, 5-6.)

An ageing management plan (AMP) is necessary for continued license approval, as it is a cornerstone for safe operation. When reaching the end of the granted operating license periods, the AMP is reviewed as part of the license renewal process. Most regulators demand licensees to implement an ageing management plan throughout the plant’s entire life cycle, as recommended by the International Atomic Energy Agency (IAEA). However, the plan can be subject to changes as operative experience is gained. (Banks et al. 2009, 8.)

The purpose of ageing management is to ensure the availability of safety critical plant systems, structures, and components (SSCs). Nuclear facilities tend to have more strictly regulated maintenance protocols than less hazardous industry due to their more comprehensive safety requirements. Ageing of safety critical SSCs is monitored closely and preventive maintenance is carried out as opposed to letting the SSCs run to failure. Life cycle management extends ageing management plans to include all plant SSCs and optimizes them for best possible economic result. (Toney et al. 2009, 7.)

Essentially, investments related to nuclear power life cycle management are continuous maintenance investments and plant modification investments. While safety SSCs take precedence over production SSCs, the time window for maintenance and modification planning is enlarged by sufficient expertise in ageing mechanics, early detection of ageing through inspection, and properly executed risk assessment. With enough time to plan, the maintenance or modification of both safety and production SSCs can be timed optimally with regards to achievability and annual budget. However, poorly anticipated risks can result in increased maintenance times, loss of production, and in worst cases, accidents or early plant closure.

This thesis is divided into a literature section and a research section. The literature section begins by introducing the main ageing management methodologies used in nuclear power, upon which the life cycle management process is built. The different steps of the LCM process are described; ageing mechanics and their detection, risk assessment, maintenance and modification planning and economic optimization. Example cases of life cycle management and asset management are obtained from conventional power utilities.

Other special features of nuclear power that impact its life cycle management are addressed next, such as long plant lifetime, as well as social and economic factors. The role of life cycle management in license renewal is explored. Some problematic modification projects related to LCM are also described. These projects are the result of inadequate technical expertise leading to loss of assets, premature shutdown and decommissioning.

As a basis for domestic benchmarking, some life cycle management methods in Finland are described. The regulatory directives given by the Finnish Radiation and Safety Authority (STUK) are also looked at.

In the research section, the TVO LCM process is described with some detail. The different phases of the process are explored, as well as the organizations involved with LCM. Problems are identified for later processing. Some future scenarios are looked at, and finally the TVO LCM model is benchmarked, where applicable, against the other models. Strenghts and weaknesses are compared and possible improvement options are considered.

2 DEFINITIONS

While the term life cycle management is normally used for a management process that aims to optimize the environmental impact of a product, the term is used here synonymously with plant life management and asset management, focusing on safe and economic management of SSC operation and maintenance. (Sonnemann & Margni 2015, 9.)

The term ageing management is used for the process of managing safety-related SSC life, as specified by regulations. Life cycle management applies the ageing management process to include all plant SSCs and implements economic optimization.

The life cycle management process consists of a technical evaluation and an economic evaluation. The technical evaluation identifies important SSCs, collects information on their performance, identifies their reliability issues, and formulates a set of maintenance and modification plans to ensure reliability over the remainder of the operating license. The economic evaluation compares the present value and future cost of each alternative plan, identifying the optimal plan for each SSC. (Sliter 2004, 23.)

3 AGEING MANAGEMENT

While most nuclear power utilities have developed their own ageing management systems, there can generally be seen to be three main methodologies. The methodologies can be categorized as experience-based, regulatory-based, and economic-based. All three methodologies are defined from a certain point of view, while a comprehensive ageing management strategy is often a combination of them. (Toney et al. 1-2.)

3.1 Experience-based

Experience-based ageing management can be seen as the oldest form of ageing management, used in general industry as well as nuclear power. This method introduces the concepts of preventive and corrective maintenance, with information about plant ageing being gathered from operative experience and shared through co-operation between companies of the same industry. In experience-based ageing management, the maintenance scope encompasses the entire plant, the goal being to maintain the functionality of all SSCs that are not classified as run-to-failure. If maintained components do fail even with preventive maintenance, corrective maintenance is carried out and the cause of failure is investigated. The maintenance plan is also corrected to ensure availability of the SSCs are compatible with the operational goals. In other words, enhancements to the preventive maintenance program are not made until corrective maintenance has to be performed. (Ibid. 2.)

However, a plant does not have to experience all unexpected failure modes in order to improve its maintenance program. Information shared between similar facilities, subsystem users and industry groups lead to everyone learning from the mistakes of one member. This way, not all facilities need to experience the same corrective maintenance, loss of production, increased radiation exposure and costs that can accompany unexpected SSC failure. (Ibid. 3.)

The first ageing management programs adapted by nuclear power utilities fall into this category. While being effective especially during the early period when many design faults and operational issues were still being worked out, experience-based ageing management has the downside of requiring things to go wrong at least once before they can be anticipated. (Ibid.)

3.2 Regulatory-based (United States)

Regulatory-based ageing management focuses on ensuring the availability of safety-related SSCs as defined by nuclear regulatory authorities. These regulations are set to ensure safe long-term operation, including life-time extensions beyond the initial design period. The regulatory-based methodology has also existed since the beginning of nuclear power, as nuclear regulators control the operating licenses of nuclear power utilities. Typically the objective for regulatory rules is to ensure the health and safety of the public. This imperative then reflects onto the rules and standards that define the design basis and operation of regulated nuclear power plants. Regulatory-based ageing management works in co-operation with experience-based management, as experience gained from older power plants are used to update and enhance regulations for continued operation of those plants as well as regulations for new power plants. (Toney et al. 3-4.)

In order to prevent unexpected safety-critical SSC failure, certain safety-specific rules have been implemented. One example is the United States Nuclear Regulatory Commission (NRC) Maintenance Rule, which imposes periodic inspection and maintenance on safety related SSCs. If SSC performance degradation is detected, the rule enforces preventive measures to be taken to reverse the trend before SSC failure. The Maintenance Rule is limited to SSCs that influence plant safety. These include directly safety-related SSCs, non-safety related SSCs that support safety-related SSCs, SSCs that support emergency operative procedures, and SSCs that would cause a scram upon failure. The Maintenance Rule does not take into account passive long-lived safety-related SSCs such as structural supports and electrical cables. These are contained in the License Renewal Rule, which provides a basis for actions required in order to ensure life-time extension and long-term operation. The NRC regulatory ageing management program also includes SSCs that support the control of five regulated events that have been deemed important to safety. These are fire protection, environmental qualification, station blackout, anticipated transients without scram, and pressurized thermal shock. It is to be noted that in Finnish regulations, explicit specifications like these are not made. Instead, the licensee is to submit an ageing management review to the authorities, the scope of which is then reviewed by STUK, the Finnish nuclear and radiation safety authority. Finnish regulations are further discussed in chapter 6.1. (Ibid. 5.)

Any SSCs that fall into the scope of the earlier mentioned objectives all require an ageing management review, which is usually carried out on a system scale. The review process typically has the following steps:

- Component materials are determined.
- Component environmental conditions are identified.
- Ageing effects caused by the materials/environment combination are determined.
- For every component and ageing effect, plant programs that manage ageing must be in place. Existing programs are to be modified if they are insufficient, or new ones developed if none exist.
- Results are validated with the help of plant-specific and industry-wide operative experience.

When implemented, the ageing management programs should monitor the condition of their dedicated SSCs by means of inspection and performance trending. Some typical programs include in-service inspection, water chemistry monitoring and flow-accelerated corrosion monitoring. Many facilities have also had to implement new methods, as the above process has shown gaps in their ageing management. Some of these methods include underground piping inspections, structural component inspections and cable inspections. (Ibid. 5-6.)

3.3 Economic-based

While the SSCs that support plant safety systems also include some that affect plant availability and production, there are still many SSCs of the latter group that are not included in the regulatory-based approach. For this reason, an economic-based ageing management method is necessary to ensure efficient production. This type of ageing management evaluates SSCs against their importance to plant availability, power production, or similar economic criteria. This type of ageing management is typically called plant life management (PLIM) as it takes into account the economic side of ageing management. (Ibid. 7.)

Economic-based ageing management also studies economic impact of ageing management, or lack thereof. Major components that affect production, such as steam generators, turbines, and generators are evaluated with the help of operative experience to predict their performance.

Preventive maintenance measures are taken to ensure optimal performance and minimize down time, combined with strategic investment plans to optimize long-term planning. (Ibid. 7.)

The process includes screening for SSCs that are critical to meeting plant goals of production. This means the prevention of downtime and unplanned loss of capacity. Once production-critical SSCs have been identified, the ageing mechanisms and their effects are determined. Data on the SSCs and their performance, ageing mechanisms, risks and safety are compiled. Depending on the evaluation results, a maintenance plan is created for each SSC. For instance, the plan can be to run proactive maintenance, keeping spares at the ready, improved preventive maintenance, improved inspection and condition monitoring, or to run the SSC to failure. The maintenance plan options are then evaluated for each component and a PLIM plan is developed. This plan includes net present value and timing for the expenses caused by each maintenance, so that optimum action timing and efficient condition monitoring can be achieved. Component-level PLIM plans are merged into system-level plans and eventually into plant-level plans. (Ibid. 8.)

The goal of the PLIM plan is to make sure each component has its value fully realized before being replaced. Replacing a component too early increases the net present value (NPV) effect of the maintenance performed. Too late replacement, on the other hand, increases the risk of premature component failure and power or production loss. In nuclear power, the loss of production also brings with it the additional regulatory costs associated with restarting. The objective is to maximize plant revenue over its entire lifetime while minimizing investment costs. (Ibid. 8.)

4 LIFE CYCLE MANAGEMENT

Life cycle management incorporates aspects from all three ageing management methodologies. Ageing management programs are an important part of the process, ensuring the operation of safety-related SSCs as in the regulatory-based methodology. Production-related SSCs are included as in the economic-based methodology. Continuous improvement of the knowledge database is executed as operative experience and technological advances are gained. The life cycle management process is divided into a technical evaluation part and an economic evaluation part. The technical evaluation is very similar to the ageing management process, but it also includes other than safety-related SSCs. The steps are usually the following:

- Technical Evaluation:
  1. Categorization. SSCs are divided into classes according to their importance to safety, production, or other criteria.
  2. Performance analysis. Which ageing mechanisms affect the SSCs, how are they monitored and mitigated? Results in knowledge of SSC condition and failure rates.
  3. Risk assessment. Analysis of SSC reliability based on failure probabilities and root causes.
  4. Maintenance and modification plans. Alternative plans are formed to ensure SSC availability over the remaining operating period.
- Economic Evaluation:
  5. Present value and future costs of each plan are calculated.
  6. The optimal plan is selected for each SSC on the basis of chosen financial indicators. (Sliter, 23.)

Alternatively, the process may be divided into an information gathering phase which includes parts 1-3 of the technical evaluation, a maintenance and modification planning phase which includes part 4, and an investment optimization phase which includes parts 5 and 6 of the economic evaluation and the eventual execution of the plans. Implementation of maintenance programs and plant modifications in turn lead to changes in plant and SSC status, which work as a feedback to the information gathering phase. This feedback is important as changes made to plant condition and new SSCs change the way upcoming maintenance and modifications are planned. For example, maintenance reduces the failure probability of a repaired piece of equipment, while replacing an old SSC with a new one might change the ageing mechanisms and failure rate associated with that SSC, as well as other SSCs linked to the same system.

The IAEA safety standards (Banks et al. 2009) specify a procedure for categorization of SSCs. This process, outlined in Figure 1, focuses on ageing management but it can also be used to identify and categorize production-related SSCs in life cycle management.

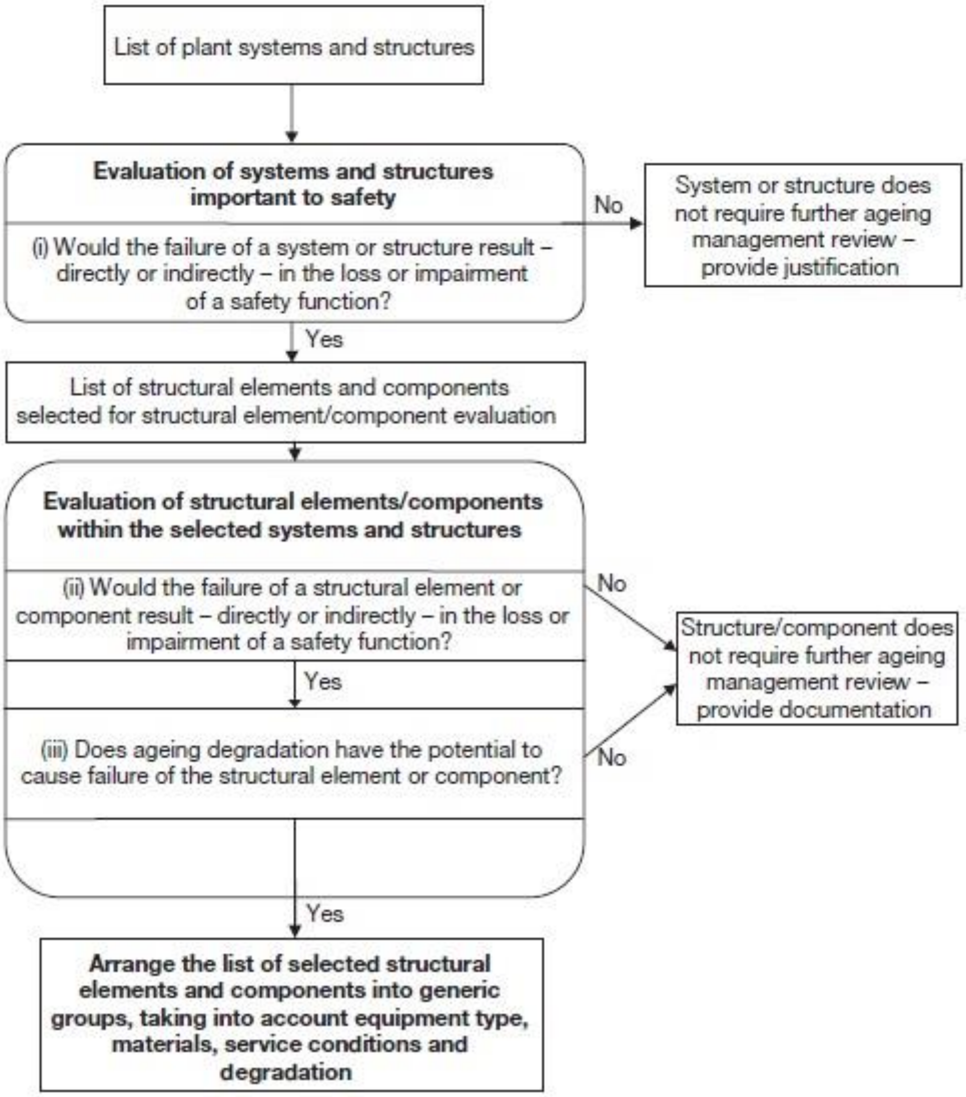

Figure 1. SSC screening process used in ageing management (Banks et al. 20).

The process also includes preliminary ageing assessment and failure consequence assessment in addition to selection of safety-related SSCs. These are used to eliminate SSCs that do not need comprehensive maintenance programs due to limited ageing effects, as well as SSCs which would not compromise plant safety upon failure. This process could be used as a categorization tool for production-related SSCs as well, by asking similar questions concerning SSC importance to power production.

4.1 Common Ageing Mechanisms

An important part of determining SSC condition and availability is to understand the mechanisms of SSC ageing. Ageing is a term that describes the change in condition of a SSC over time. Ageing can be either physical or technological. Physical ageing is the degradation of material properties due to operating conditions or environmental damage which increases likelihood of SSC failure. Technological ageing, or obsolescence, is the process of the SSC becoming obsolete in comparison to current standards, regulations and technology. Changes in operative requirements and loss of spare part production or technical support also contribute to obsolescence. (Ramírez et al. 2013, 330-331.)

There are several ways for a SSC to experience physical degradation. Most of these are related to the operating conditions and environment of the SSC. One typical ageing mechanism is corrosion, which is caused by chemical reactions taking place on the surface of a material under certain environmental conditions. Corrosion can lead to material degradation and loss of thickness, as well as increase the susceptibility of the material to stress corrosion cracking, if the material is also subjected to tensile stress. Mechanical corrosion, also known as erosion, can occur when particles suspended in flowing fluid impact the surrounding material, causing wear (Horrocks et al. 2010, 8-14). Components subjected to alternating mechanical load or temperature experience fatigue, which increases the material's susceptibility to cracking. This can be further exacerbated by corrosive conditions. Metals experience embrittlement when subjected to neutron radiation, where neutrons displace lattice atoms and weaken the lattice structure, leading to brittle material properties. (STUK 2014, 15-17; Boyne et al. 1992, 35.)

Ageing can be detected through visual inspections and non-destructive testing. Inspection techniques include direct visual observations of the material, ultrasound inspections, radiographic inspections, and other methods capable of detecting cracks or measuring material thickness (Horrocks et al. 8-18). Monitoring operating conditions, such as temperature, irradiation, stress cycles and water chemistry provide insight into the ageing effects that the operating environment may have on the SSC. (IAEA 2015, 3-4; 2013b, 2-3; 2013c, 2-3.)

Mitigation of ageing can be done primarily through proper material selection according to the estimated operating conditions during the design phase. If unexpected ageing occurs during operation, attempts can be made to improve the operating conditions to slow down ageing, for example by improving the water chemistry or changing the reactor loading pattern (Boyne et al. 28). However, eventually the ageing mechanisms will result in SSC failure, and repair or replacement will be in order. Whether the SSC is repaired or replaced before failure occurs is a matter of maintenance and modification planning, discussed later on in chapter 4.3. (IAEA 2015, 3-5; 2013a, 2; 2013b, 2-3.)

Technological ageing, or obsolescence, of SSCs can occur in several different ways. There is also a difference between the obsolescence mechanics of systems, and the obsolescence mechanics of structures and components. System obsolescence is mainly related to changes in regulations, as requirements for safety aspects, redundancy and diversity determine whether a system is up to date or not. For example, a system with two redundancies can become obsolete if regulations change to require four redundancies, regardless if the system is in good physical condition. Obsolescence of structures and components is related to market supply changes. Evolution of technology can drive manufacturers out of business, or update their device models so that the original device is no longer available. This is an example of loss of spare part supply or tech support, which leads to component obsolescence. New, more efficient technologies also contribute to obsolescence, if such technology becomes available that materially contributes to improved safety, condition monitoring or maintenance. However, although a new component or structure may reduce the failure rates of old failure mechanics, there can be unexpected new failure mechanics that need to be identified. (STUK 2014, 22.)

All cases of SSC obsolescence would mean that the SSC has to be replaced with a new or upgraded version of the SSC that would meet the requirements of current standards or regulations, latest level of technology, or that would have access to technical support and spare parts.

4.2 Risk Assessment

A risk assessment is conducted to determine the probability and significance of SSC failure. There are several different risk assessment techniques available, but most can be categorized as either deterministic or probabilistic. Deterministic risk assessment uses point estimates for failure probabilities, such as failure rates, while probabilistic risk assessment (PRA) uses statistical methods, such as probability distributions or Monte Carlo simulation. Both have their advantages and disadvantages; deterministic methods can be used for quick risk identification and can be used for design basis risk assessment, while probabilistic methods give more accurate results but are more time-consuming processes. (Torres et al. 2015, 484-485.)

In nuclear power, PRA is preferred due to its more accurate best estimates. The PRA model consists of the following parts:

- Event Trees: Used to model the sequence of events from an initiating event to an end state, or consequence.
- Fault Trees: Used to model the failure of safety systems or other mitigating functions. Fault trees include all components or dependencies that a mitigating function requires to operate.
- Event frequency and probability estimates: Data on component failure rates and other event frequencies that is used in the event and fault trees. (Ibid.)

First, events leading to the analyzed end result are identified and modeled by event trees. Accident sequences are found in the event trees, where the different combinations of conditions leading to the end state are identified. Certain mitigating functions are further modeled by fault trees, where the dependencies of the functions are listed. From the fault tree, failure sequences known as cut sets are identified. The cut sets describe all combined conditions that may lead to failure of the function. The probabilities of the cut sets can be used to calculate the failure probability of the mitigating function, which is then transferred to the event tree. Examples of simple fault and event trees can be found in Appendix I. (Ibid.)

Failure probabilities of fault tree components and frequency of other events in the event trees are obtained from operative experience, manufacturer data, plant design, engineering analysis, human reliability analysis (for operator errors), maintenance procedures (changes to failure probabilities due to repairs) as well as experts and research. The failure probabilities are modelled with probabilistic methods, using probability distributions, Bayesian analysis, or Monte Carlo simulation for best estimate values. From the results, the contributions of certain events or component failures can be compared to the total end result frequency, in order to identify the weakest links in the system that require improvement or special attention with regards to maintenance. As with any computer analysis attempting to model the real world, there are uncertainties with PRA, which is why the results are often presented as probability distributions instead of exact values. Safety margins are imposed on the basis of the distributions. The safety margins can be reduced by more accurate, enhanced models, through incorporation of research results, and by collecting additional data on components and events. (Torres et al. 484-485; United States Nuclear Regulatory Commission 2016.)

Nuclear power PRA results are categorized as three risk levels. Level 1 PRA estimates the frequency of reactor core damage due to accidents, commonly known as Core Damage Frequency (CDF). Level 2 PRA further models core damage accidents, estimating the frequency of accidents that result in radioactive releases from the power plant. Level 3 PRA models the consequences of level 2 PRA releases and estimates the injury caused to the public and damage to the environment. With the help of PRA, SSCs or events that contribute most to CDF can be identified. It is then further assessed whether improvements to safety can be achieved by addressing these SSCs or events. (United States Nuclear Regulatory Commission 2016.)

In order to reflect the current status of the plant, the PRA also needs to be updated whenever new information becomes available, such as changes in operating conditions, SSC ageing progression, regulatory requirements, modifications or new SSCs. The process of updating the safety analysis has become known as living PRA, and is now standard procedure on many nuclear power plants. This can be used to more accurately assess SSC risk level when planning replacement investments, as the probability of failure will depend which stage of life the SSC is in. Constant failure rates can still be assumed in certain cases, such as when planning periodic maintenance or reliability improvements. Failure and event trees regarding single SSCs are expanded and added into larger trees which describe larger systems. The failure significance of a single SSC can be derived from the larger trees, as its contribution to CDF can be calculated and compared to total CDF. The risk significance of the SSC can be seen as the combination of failure probability and failure significance. The risk significance can be assigned a corresponding value, or index, that can be used when comparing SSCs for maintenance or modification investments. CDF is a typical end state consequence used in nuclear power PRA, but one can also conduct the analysis for other end states, such as power level reduction or production loss. (Perryman et al. 203-205; Adamec et al. 2001, 1-8; Sliter 107-111.)

4.3 Maintenance and Modifications

It is important to determine what the allowed unavailability of an SSC is when forming a maintenance plan. Safety- and production-related SSCs preferably have low unavailability, and therefore are often subject to preventive maintenance strategies. Other SSCs can be afforded to run until failure, upon which they are either repaired or replaced according to which is more economically viable. Condition monitoring and inspections are also included in the maintenance plan according to SSC importance. (Maintenance Assistant 2016a.)

The need for inspection and maintenance often varies over the lifetime of the SSC. Wintle et al. (2006) divide SSC lifetime into four stages: initial, maturity, ageing and terminal. Each stage correlates to the age of the SSC, the amount of accumulated damage, its failure probability, and its fitness for service. The maintenance and inspection rates are determined according to life stage. A graph indicating the failure probability of SSCs across different life stages is shown in Figure 2. (Ibid. 44-46.)

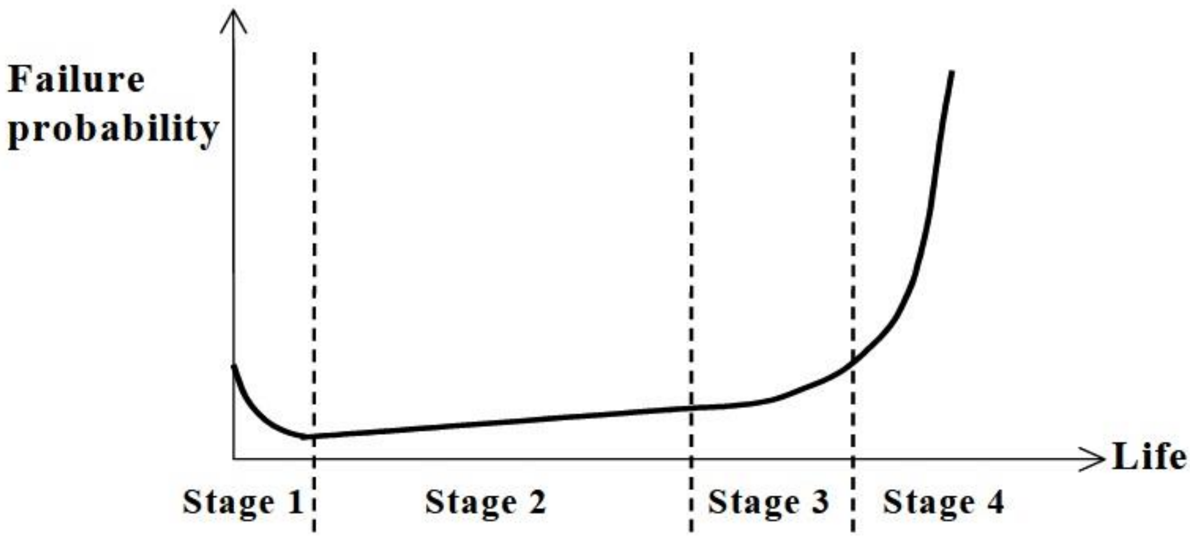

Figure 2. Model of SSC failure probability across the four life stages (Wintle et al. 44).

Stage 1 is the initial or post-commissioning stage when the SSC is first put into service. This stage experiences some increased failure probability due to unexpected design faults, material or fabrication issues. These unforeseen issues can cause the SSC to rapidly degrade in its early life and progress to the later stages. The SSC can also have been incorrectly installed and thus experience leaking valves or seals, or have loose bolts etc. These initial issues are identified and addressed by comprehensive post-installment inspections. The timing of these inspections are determined by the factors that might contribute to early deterioration and their time of onset after operation has begun. (Ibid. 46-48.)

Stage 2 is the maturity or risk-based stage when the SSC has progressed past its early life problems. In this stage the SSC experiences predictable deterioration and relatively few issues that require attention. Periodic inspections are used to confirm the rate of deterioration, and the frequency of these inspections can be determined by risk analysis. Operative experience is used to update the risk analysis procedure. Routine maintenance is used to fix minor problems. (Ibid. 47-48.)

Stage 3 is the ageing or deterministic stage when the SSC has accumulated some damage and the deterioration rate increases. The extent of the damage needs to be evaluated quantitatively and the remaining life of the SSC needs to be estimated. Obsolescence also contributes towards putting the SSC into stage 3, as there might be changes in operating conditions that do not fit the design margins. Inspection and maintenance needs to become more proactive at this stage, when design margins start to become less accurate and focus shifts towards a fitness for service approach. (Ibid.)

Stage 4 is the terminal or monitored stage when the SSC damage becomes increasingly severe and the SSC soon requires major repairs, decommissioning or replacement. The degradation rate is increasingly rapid and unpredictable. This stage requires increased on-line monitoring of the damaged areas or more frequent non-destructive testing to monitor the size of flaws until they reach maximum tolerable levels. At this point, a reduction of operating conditions severity might be in order to ensure operability. (Ibid.)

There are several different maintenance strategies that can be considered, depending on how the SSCs have been categorized according to their importance to safety or production. The most common maintenance strategies are corrective and preventive maintenance. (Maintenance Assistant 2016a.)

Corrective maintenance means the SSC is not repaired or replaced until first occurrence of failure; this is also called run-to-failure, breakdown, or reactive maintenance. Corrective maintenance is typically afforded to SSCs that are of minimal importance to safety or production, which can be allowed some unavailability without compromising safety systems integrity or losing production. Run-to-failure SSCs are typically repeatedly repaired at the time of failure until their condition deteriorates enough to warrant a replacement, for example when failure intervals become short enough that repair costs exceed the cost of a replacement. (Ibid. 2016b.)

Preventive maintenance is performed in order to reduce the failure probability of an SSC. The difference from corrective maintenance is that preventive maintenance is carried out during SSC operation, before failure occurs, and often on a regular schedule. Preventive maintenance is typically afforded to critically important SSCs that cannot be allowed to experience unavailability, or have certain failure modes that can be reduced through regular maintenance. (Ibid. 2016c.)

Plant modifications are also integral to life cycle management. The introduction of new SSCs or modification of old ones becomes relevant as the plant ages, both physically and technologically, as well as when new regulations come into effect. Modifications can also be justified by significant value increases, such as energy efficiency, increased production, or reduced maintenance needs. In nuclear power, modifications are also closely related to long term operation plans and life time extension projects. Modifications can be seen as a separate process from maintenance, more akin to the design process than operation. The need for modifications can arise from something as simple as obsolescence, if an SSC has become outdated and lacks both tech support and spare parts. A replacement SSC must be found, that fulfills all the same tasks as the old SSC without introducing new vulnerabilities. In nuclear power, this might involve a lot of licensing and feasibility studies if the SSC is safety-related. Modifications are typically implemented as separate projects, whereas maintenance is a continuous process. (Davenport et al. 2001, 1, 9-10.)

4.4 Economic Optimization

Economic optimization of maintenance and modifications is the final step in the life cycle management process. This optimization can be done from the SSC level up to the plant level. The goal is to minimize maintenance costs while maintaining the required availability of the SSC. Corrective maintenance typically has less direct costs than preventive maintenance, as it does not require any maintenance work until the time of SSC failure. However, there are indirect costs related to SSC unavailability, if production is affected. Preventive maintenance costs are higher due to the larger amount of work incurred by periodically maintaining the SSC in question. Therefore, preventive maintenance needs to be justified either economically or by safety availability criteria. (Maintenance Assistant 2016b; 2016c.)

Preventive maintenance can be optimized by also conducting predictive maintenance. Predictive maintenance aims to identify failure indicators and thus estimate when an SSC is about to fail. This information can be used to better schedule preventive maintenance measures, making the maintenance intervals as long as possible and thus increasing cost-efficiency. In essence, predictive maintenance aims to move preventive maintenance away from a time-based method to a condition-based method. Different condition-monitoring techniques are used as a part of predictive maintenance, however they also incur costs of their own. (Ibid. 2016d.)

SSC condition is determined through different tests, inspections, or online monitoring. Testing and inspection often requires taking the SSC offline for the duration, while in-service inspection and online monitoring methods can be quite expensive. The value gained from inspection needs to outweigh the cost. In other words, the cost of predictive maintenance measures must not exceed the cost savings gained from reduced maintenance intervals. The most critical SSCs can be afforded on-line condition monitoring, but for others periodic tests and inspections may be in order. The timing of periodic tests and inspections can also be optimized. One method has been proposed by Vaurio (1995), where the testing and maintenance (T&M) interval is optimized to achieve minimum costs with maximum allowed unavailability. The maximum allowed unavailability is derived from regulations or production risk decision making. Vaurio's method analyses unavailability and cost as functions of the T&M intervals. Unavailability is decreased with more frequent T&M, but at the same time costs are increased. The unavailability and cost rate curves are shown in Figure 3. (Vaurio, 23-25; Sliter, 107; Maintenance Assistant 2016d.)

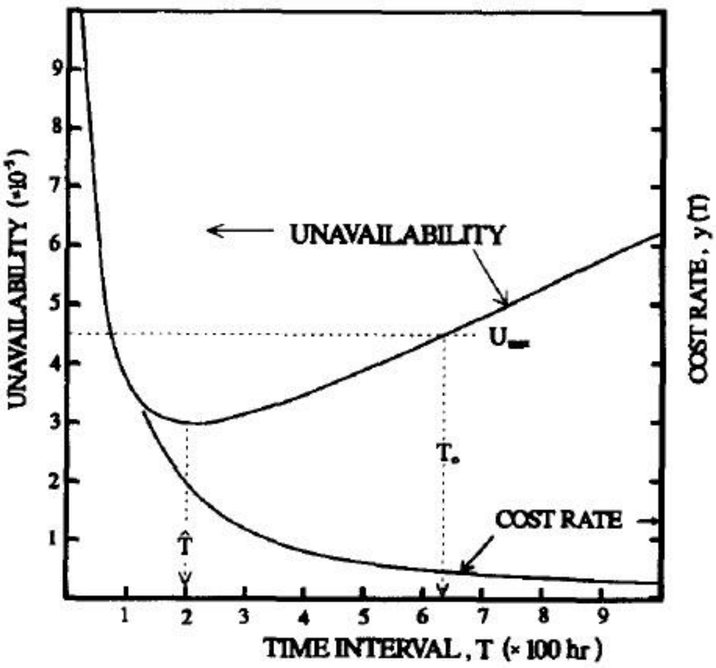

Figure 3. Unavailability and cost rate as functions of testing and maintenance time intervals (Vaurio, 25).

From Figure 3, one can see that minimum unavailability is achievable with T&M interval 200 hrs. However, the cost rate is quite high at that point. If maximum allowed unavailability, defined as $U_{\max}$, is higher than minimum unavailability, it can be found to be more economically viable to use a longer T&M interval. In this case, the optimal T&M interval is between 600 and 700 hours, where costs are about 1/4$^{\text{th}}$ of the costs of minimum unavailability.

Reliability centered maintenance is another optimization strategy that aims to prioritize maintenance procedures so that system functions are preserved. Normally, this would include only production-related systems, but for nuclear power also safety systems are considered. Reliability centered maintenance uses risk assessment techniques to identify the failure modes that affect system functions and prioritizes maintenance that mitigates those failure modes. This is a form of precision maintenance that also reduces maintenance costs through prioritization of components that contribute most to unavailability, instead of performing more extensive, overall maintenance on the entire system. (Maintenance Assistant 2016e.)

Modification projects can also be optimized. As indications for modification needs can appear long before the actual implementation is necessary, there can be plenty of time to plan the modification project. Different technological alternatives can be considered. As part of the investment planning process, modification projects proposals should be considered with sufficient expertise, and their introduction into the investment budget should be timed in such a manner that maximum value is gained from the investment. This means replacing old SSCs only at the very end of their lifetime, and evaluating the necessity of completely new SSCs when considering the remaining lifetime of the plant. Resource allocation is also a factor that needs to be considered when prioritizing modification projects. Projects of lesser importance can be delayed in favor of more important ones that require larger amounts of manpower.

4.5 Example Processes

This chapter presents a few examples of the processes used in industrial asset life cycle management, in which economic indicators are used for investment decision making and how the indicators are prioritized. Some case examples are also provided and can be found in the appendices.

The processes generally involve the selection of parameters that are used in decision making. The parameters usually relate either to economy or safety. Typical parameters are risk score, net present value change, revenue at risk, and benefit-to-investment ratio. Risk scores are usually calculated through risk analyses. Depending on the case, the failure rates used can either be constant or time-dependent. Uncertain values are often sampled by Monte Carlo simulation.

4.5.1 Hydropower Asset Management Program

One example life cycle management process is the one introduced by HydroAMP (Bachman et al. 2006), which details the process used for hydropower asset management. This process includes condition indexes which are used to rank components according to their condition. Condition value is determined through physical inspections, tests and measurements, component operation and maintenance history, and component age. Components are also assigned a weighing factor depending on their importance to power production, which are used to modify the condition ratings. The modified ratings are used to generate condition indexes for individual units and stations. Examples of condition values and modified condition ratings contributing to the unit- and station-wide condition values can be found in Appendix II. (Ibid. 6-7.)

In combination with cost, consequence and risk assessments, the unit condition assessments provide the necessary information for maintenance prioritization and investment planning. There are two types of analyses outlined that determine a risk-based investment decision process. The first type focuses on equipment condition and cost alone, while the second type also accounts for the consequences of action and inaction. (Ibid. 14-16.)

Type 1 analysis can be used when planning the maintenance and investments related to cheaper components. This analysis focuses on six cost and condition factors:

1. Total Cost: All costs involved with repair or replacement of a component, such as engineering, administration and commissioning.
2. Current-Year Cost: Portion of the investment cost used for the current year.
3. Incremental Annual Maintenance: The increase or decrease in maintenance caused by the investment.
4. Achievability: Possibility to undertake the project during the current timeframe.
5. Project Phase: Which phase of the project is being analyzed: study, engineering, procurement or construction.
6. Condition Index: The most recent condition index derived from the methods shown in Appendix II. (Ibid. 15.)

This type of analysis can be used for situations like emergency corrective maintenance, in case of failures, and when analyzing auxiliary systems. Without budget constraints, the investment prioritization can usually be determined simply from the condition rating. For more expensive equipment, however, also the consequences of maintenance actions (or lack thereof) need to be examined. Type 2 analysis includes the following factors in addition to the ones in Type 1: (Ibid. 15-16.)

1. Marginal Value of Generation: Annual value determining the contribution of a component to energy production.
2. Total Outage Duration: Length of time it takes to restore a unit to production after failure.
3. Revenue at Risk: Loss of revenue due to the repairs, this is the marginal value of generation multiplied by total outage duration.

4. Risk Map Score: Measures the total risk of failure depending on component condition rating and the consequences of its failure. Example in Table 1.
5. Other Business Factors: Other factors impacting decision making, such as environmental, legal and safety considerations.
6. Priority Rank: Urgency of the project, this rank is achieved by adding the other business factors to the risk map score.

Table 1. Risk Map. Evaluated components are situated in one of the indicated risk level zones depending on their condition and consequence values. (Bachman et al. 17.)

	Condition Index	Condition Value	Risk Map										Risk Level Results
Poor	0 to 0,9	10	11	12	13	14	15	16	17	18	19	20	High
	1 to 1,9	9	10	11	12	13	14	15	16	17	18	19	17-20
	2 to 2,9	8	9	10	11	12	13	14	15	16	17	18	Medium-
Fair	3 to 3,9	6	7	8	9	10	11	12	13	14	15	16	High
	4 to 4,9	5	6	7	8	9	10	11	12	13	14	15	13-16
	5 to 5,9	4	5	6	7	8	9	10	11	12	13	14	Medium
	6 to 6,9	3	4	5	6	7	8	9	10	11	12	13	9-12
Good	7 to 7,9	2	3	4	5	6	7	8	9	10	11	12	Medium-
	8 to 8,9	1	2	3	4	5	6	7	8	9	10	11	Low
	9 to 10	0	1	2	3	4	5	6	7	8	9	10	5-8
	Consequence Value		1	2	3	4	5	6	7	8	9	10	Low
	Risk Level		Low		Medium-Low		Medium		Medium-High		High		1-4

The risk map in Table 1 is based on component condition index and consequence of failure. The consequence used in this particular table is loss of revenue on failure (Ibid. 16). If no other business factors are taken into account, the Priority Ranking of components can be done directly by looking at which risk zones each evaluated component falls into. An example of investment planning using the Type 2 analysis can be found in Appendix II.

This type of risk-informed economically optimized maintenance planning is a good way to ensure best possible return on investment. In nuclear power, there is also the added condition of regulatory demands, which would influence the Risk Map Score and Priority Ranking of SSCs, should one decide to take this approach to life cycle management.

4.5.2 EDF Durability Method

French state-owned electric utility Électricité de France (EDF) has developed a process for fossil power plant asset management. This process, called the Durability Method, is based on probabilistic evaluation and can be done on a component level, plant level or fleet level basis. The goal is to find the optimal life cycle management approach, so that correct investments are done to satisfy security, availability and production needs at the optimal time. The component level analysis is generally done for major power generation components such as the steam generator (boiler), turbine, generator and condenser. (Benetrix et al. 2009, 236-238.)

The process has three major steps (Ibid. 239):

1. SSC-file elaboration: Main risk events are identified, as well as mitigation actions.
2. SSC-scenario building: Events and mitigations are combined into scenarios with the help of probability distributions.
3. SSC-evaluation: Scenarios are compared with the help of probabilistic technical and economic indicators.

SSC-file elaboration consists of compiling the available technical knowledge for each SSC. It is comprised of knowledge of condition, ageing, maintenance, operating conditions, regulations, obsolescence etc. The main risk events that can occur during the SSC's lifetime are identified, as well as preventive or corrective actions that can be taken to mitigate the effect of these events. (Ibid.)

SSC-scenario building consists of creating scenarios for each relevant event, containing the mitigation actions and strategies related to each event. Each event is associated with its probability distribution of occurrence over time; this is done in order to account for the factors that are difficult to predict and that impact event occurrence. The mitigation actions are also quantified; material and labor costs are estimated as well as the impact that mitigation actions have on the probability of occurrence. (Ibid.)

Finally, each of the scenarios are compared to a reference scenario, which is the scenario that would be chosen if SSC analysis was not performed. Several indicators are computed which help the decision maker to choose the optimal scenario. One of the most important indicators is the NPV, which is calculated with a dedicated tool based on Monte Carlo simulation. As the

NPV distribution of each scenario is obtained, the decision maker can make the optimal decision based on the main values such as mean and extreme NPV values, and the probability that scenario will be non-profitable. An example of this method in action is presented in Appendix III. (Ibid.)

4.5.3 Westinghouse Proactive Asset Management

Westinghouse has developed a proactive asset management (PAM) tool that can be applied to life cycle management studies, providing projected financial results of alternative maintenance strategies. The alternative LCM plans are compared with a base case, with the main comparative financial indicators being the NPV change and the benefit to investment ratio. The NPV change is the sum of present value cost savings from lost power generation, corrective maintenance and preventive maintenance when comparing each alternative strategy with the base case. The benefit to investment ratio indicates the ratio of dollars saved per dollars invested. The tool incorporates uncertain variables and provides the results as probability distributions to enable risk-informed decision making. (Sliter, 97-100.)

The key strategies used and compared by the PAM tool include the following:

- Run to failure: Replace the SSC once it fails in service, fails an inspection or fails a test.
- Periodic replacement: Replace the SSC periodically at an optimal frequency before it fails.
- Improved maintenance: Improve the efficiency of current condition monitoring or preventive maintenance.
- Spare parts: Improve service cost savings and shorten maintenance unavailability by procuring spares for the SSC.
- Upgrades: Upgrade an obsolete SSC to a more efficient or reliable one. (Ibid. 103.)

Run to failure is presumed to be the base case scenario unless it is otherwise specified. Often it makes economic sense to use this type of corrective-only maintenance when its costs are less or not sufficiently larger than preventive replacement. Inspections are still included in the costs, as the failure of a test or inspection counts as SSC failure. Corrective maintenance typically has longer outage times than the proactive strategies, a higher unplanned failure probability and higher replacement power costs. Calculations are done on the basis of estimated failure rates and economical inputs such as outage hours, equipment costs, labor costs, replacement power costs due to unplanned outage, etc. (Ibid.)

Periodic replacement aims to replace the SSC before it fails, depending on its years of service. The optimal time for replacement is calculated through failure rates of the old and new components, replacement costs, outage hours caused by failure and costs related to failure. While many SSCs have scheduled replacement plans, it has been found that many that are important to power production do not, and thus a preventive maintenance plan can result in significant asset value increase. (Ibid. 104.)

Improved maintenance evaluates existing preventive maintenance, aiming to extend the lifetime of a SSC. The results can be initial one-time investments, such as procurement of tools or personnel training procedures, as well as changes in the ongoing yearly costs. While an improved condition monitoring program can give better indications of impending SSC failure, it does not impact the reliability of a SSC. Improved condition monitoring instead aims at effective monitoring to assist in the planning of replacements or repairs at the next convenient outage. This can lead to reduced preventive maintenance costs. The improved condition monitoring model optimizes inspection frequency to determine the probability of detecting ageing before in-service failure. An example is shown in Figure 4, where the loss of wall thickness is plotted over time with periodic inspections. Each periodic inspection has a probability to detect the ageing mechanism. (Ibid.)

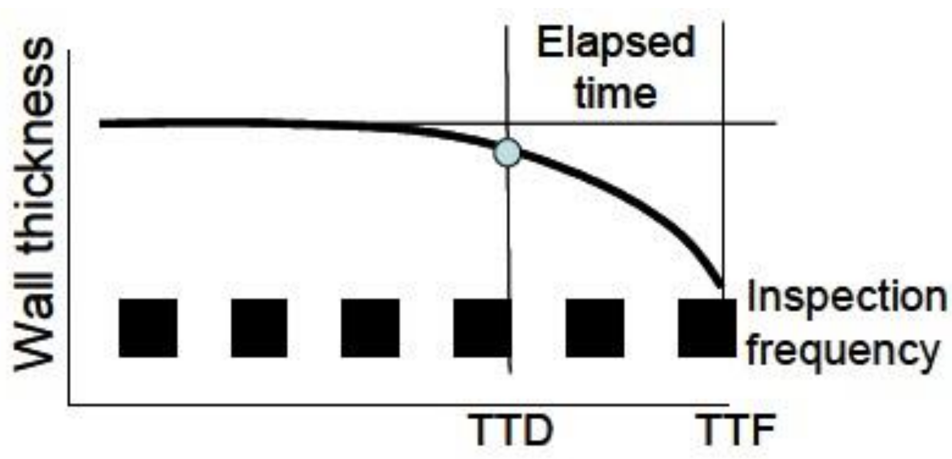

Figure 4. PAM condition monitoring improvement model: Wall thickness degradation over time with periodic inspections. TTD = Time to Detection, TTF = Time to Failure. (Sliter, 105.)

Optimization of monitoring includes considerations of when the improved monitoring program is to begin, the new inspection frequency, the likelihood of detectable degradation being present at each time period, the likelihood that the inspections will detect the degradation, the consequences of undetected degradation and the costs of the inspections and tests. As one can see from Figure 4, the periodic inspections can provide a window of opportunity to prevent failure. However, the test frequency and precision of instruments does not necessarily mean there will be enough time after detection to prevent the failure. Also, the consequences of failure may not be costly enough to warrant the inspections, even if they provide with early failure indicators. (Ibid. 105.)

The spare parts strategy is a modified run to failure strategy where a spare SSC is procured in advance while waiting for its in-service counterpart to fail. When failure occurs, the replacement incurs lower costs than would otherwise be the case mainly due to shorter outage time. Optimization aims to identify the best year in which to purchase the spare. If a SSC does not suffer significant degradation until after several years of operation, it more costly to purchase the spare during the first years of its operation than later, closer to the likely failure event. The PAM tool uses ageing and failure rates, spare costs and failure consequence costs to estimate the optimal time for purchasing the spare. (Ibid. 105-106.)

The upgrades strategy aims to upgrade to a more reliable SSC in order to provide benefit for a one-time investment. The upgraded SSC should ideally have reduced maintenance costs and better availability than the old one and not introduce new vulnerabilities. Optimization includes comparing upgrade costs with changes in periodic maintenance costs and production losses. (Ibid. 106.)

The PAM tool uses two main modules, the constant failure rate module and the age replacement module. The constant failure rate module is used for reliability improvement strategies, while age replacement deals with optimal replacement time calculations, where a constant failure rate cannot be assumed. An example of the constant failure rate model in action solving a standard problem is presented in Appendix IV. (Ibid. 107.)

5 ADDITIONAL FEATURES OF NUCLEAR POWER

Many nuclear power utilities struggle with additional factors involved in their life cycle management and investment planning. The long design lifetimes of nuclear power plants mean that significant changes in technology and regulations may occur and lead to new investment needs. Social and environmental factors also play their part to increase or decrease costs related to future investments. A negative public opinion can eventually lead to political pressure, which can in turn lead to increased regulation and stricter safety margins or increased inspections, monitoring or maintenance demand. A high capacity factor, good plant availability and few incidents lead to greater public trust and enhance the company image. Investments that positively impact public relations are to be valued, as they might ease the path for coming projects such as possible long term operation and license renewal.

License renewal is something many utilities are considering as their plants approach the end of their design life. Due to the conservative regulations many nuclear power plants have been operated and maintained in very good condition. As operative knowledge accumulates many plants have been discovered to have the potential for much longer life times than originally anticipated.

However, extended operation often requires major modifications to the plant in order to make sure that long term operation can be carried out safely. If the effects of these modifications are not understood completely, there can be very unfortunate complications. Some of the complications that have been experienced, and their consequences, are presented later on in this chapter.

5.1 Plant Lifetime

Nuclear power plants typically have long lifetimes, having been designed to operate for 30 or 40 years at least. The long lifetimes mean that significant changes in technology and society may occur during this period. The impact of these changes can be seen as increased regulation as well as SSC obsolescence, leading to unexpected upgrade and investment needs. Some of these can be seen as experience-based improvements of safety equipment, as a result of safety issues or accidents at other NPPs. Examples of accidents that resulted in safety upgrades are the Three-Mile Island incident, which influenced mainly Western reactors, and the Chernobyl accident, which influenced mainly Eastern reactors (World Nuclear Association 2015). The

Fukushima accident lead to systematic safety reviews in NPPs around the world in order to discover vulnerabilities to similar external hazards. This meant another round of safety-related SSC investments. (OECD 2016, 20.)

Evolving regulations may also incur investment needs as safety systems may no longer live up to the required standards. Government policies may also change during the lifetime of the NPPs. Continuous updating of regulations and safety procedures can be seen as a part of the safety culture involving the nuclear industry. (STUK 2016, 19.)

5.2 Social and Environmental Factors

Nuclear power divides opinions in the public and the political field. The opposition of nuclear power is generally based on the feeling of fear that radiation and radioactive waste evokes in the public. While experts rate nuclear risk as low compared to other dangers, such as automobile or air travel, they generally use quantifiable risks such as annual mortality rates as a basis for their comparison. The public also considers the uncertainty, unknowability and possible catastrophic results of the risks and as such tend to rank nuclear power as riskier than other dangers. This is hard coded into social structures, a preference for stability and controllability while fearing the unknown. Due to perceived catastrophic results of nuclear power accidents, it is unlikely that the public will change their views even when presented with statistical evidence comparing mortality rates between different power production technologies or other dangers. Even though immediate mortal danger is not present even in severe accident situations, people are worried they might have to possibly permanently leave their homes. There is also a fear of the long-term effects, whether exposure will lead to cancer later on. (Parkins & DeLay 2011, 3-5.)

Continued demonstration of safe and reliable operation, low emissions, as well as transparent and frequent dialogue with the public will work to slowly increase trust in the industry. Trust, on the other hand, is destroyed easily by secrecy or a feeling of exclusion from the public. This is a factor that increases the importance of safety-related SSCs in investment planning, as public opinion can have long-reaching effects, especially when it comes to political and economic decision making regarding nuclear power. (Ibid.)

The power of social opposition has been demonstrated in the past, where opposition groups have managed to significantly slow down or stop the development of nuclear power. In California, in the 1960s and 1970s, local public opposition of nuclear power was significant enough to create new social values against the entire industry. These values managed to permeate even the scientific community, eventually leading to decision makers stopping the entire development process. Similarly, a small German environmentalist group managed to cause several investors to back out of a nuclear generation project in Bulgaria, as the banks saw the negative reputation risk as too high for continued investment backing. (Ibid. 16-17.)

Social influencing of political decision making can be significant, but there is also existing political anchoring related to political affiliations or ideologies. In these cases, certain political groups adhere to rigid values regardless of their knowledge of nuclear power. Increased lobbying or information spreading by experts would not easily contribute to changing of opinions. As governmental compositions change over the years, the industry may find itself faced with strong political opposition or more favorable views. A demonstrated safe and reliable operation without secrecy would be an effective tool to negate opposition. 'What if'- dialogue should be addressed seriously with comprehensive worst-case scenario plans and accident mitigation strategies in place that can be used to demonstrate how limited and controllable the consequences of accidents are. (Ibid. 5-6.)

Special care should also be given to SSCs preventing or reducing environmental release of radioactive substances. While waste heat emissions from the cooling system have a greater effect on the local environmental conditions around the plant, the radioactive emissions are typically the ones which receive most media coverage and public interest. Due to the fear-inspiring nature of ionizing radiation, strict control and monitoring of these emissions can serve to further improve public trust. The emissions can be categorized as operational and accidental emissions. Operational emissions are such radionuclides that are routinely released during normal operating conditions. These are typically gaseous, such as xenon and krypton, and liquid, mainly tritiated water. All three are examples of substances that are notoriously difficult to contain due to the inert nature of noble gases and practical difficulty of distinguishing or separating hydrogen isotopes. SSCs contributing to the containment or emission reduction of these substances should receive extra importance during maintenance and investment planning, as increased emission levels can lend support to socio-environmental protest forces. However, the effect of nuclear power in combating climate change can be a powerful tool in gaining both public and political approval. (Paschoa 2009, 6-7.)

A good example on the environmental, social and political factors affecting nuclear power can be seen in Sweden's nuclear power policies. Sweden has passed decisions on phasing out nuclear power based first on political motivations in the 1980's and later on economic motivations. Opposition of nuclear power originated from the Three Mile Island accident, leading to an initial referendum for phasing-out and decommissioning all nuclear power in 1980. The Chernobyl accident further accelerated these plans. The debate has continued since, with nuclear proponents sometimes managing to overturn government decisions with economic arguments. However, the political atmosphere remained mostly negative through the 1980s and 1990s with two units being closed 1999 and 2005, due to pressure from Denmark as the power plants were situated only about 30 km from Copenhagen. A heavy tax was also imposed on nuclear energy production, and the construction of new units was banned. In 2006, a more positive atmosphere began to form with major reactor upgrades being allowed to replace the lost capacity and later on even the new construction ban being removed. The reason for the shift toward a more positive attitude lies mainly in the concern for global warming becoming a higher priority than the risks associated with nuclear power. The Fukushima accident had a further detrimental impact on public trust. Recently, the political atmosphere has shifted again toward a more pro-nuclear view, as an agreement on the phase-out of the nuclear tax was announced. This agreement also allows the construction of up to ten new nuclear reactors at existing sites, to replace old reactors as they are decommissioned. (World Nuclear Association 2016.)

5.3 License Renewal & Life Time Extension

The operating license periods vary from country to country. For example, U.S. NPPs were granted long operating licenses that coincided with their original design life time. License renewal in the U.S. equals design life time extension. In Finland operating licenses were initially only granted for 5-10 years and later on for 20 years at a time, while NPP design life times were longer, up to 40 years. This means that NPPs in the U.S. have been run with AMPs based on design life time criteria, while Finnish NPPs have had their AMPs regularly evaluated together with other reviews each time a new operating license has been applied for. In addition, the newer 20 year licenses required a safety review, including AMP re-evaluation, after the first 10 years. So the definition of license renewal is different depending on which country is being studied. In the U.S., license renewal is not done unless life time extension is desired, while in Finland, license renewal is done periodically during the design life time of the plant. (United States Nuclear Regulatory Commission, 2015; TVO 2009, 5-8.)

Life time extension is usually considered because current nuclear power plants approaching the end of their design life were generally designed, built, operated and regulated by very conservative standards, leading to significant safety margins. This combination of conservative design and operation is an essential background for continued safe long-term operation (LTO), extending beyond the initial design life. Operative experience and research that has been gathered over the years has also expanded knowledge of ageing mechanisms beyond what was known at the design time. With the help of this knowledge, as well as current engineering technology, it is possible to assess the technological feasibility of safe LTO. (Blaiohanu et al. 2008, 5.)

LTO feasibility is evaluated through a separate study, which considers strategic elements, such as demand for electricity, regulatory requirements, current physical condition of the power plant, including need for modifications and procedures necessary for continued safe operation, environmental impact, and economic feasibility. (Ibid. 7.)

The process for evaluating current ageing management programs involves making sure that current license basis requirements are continued in the planned LTO period. The process has three main steps:

1. Screening for safety-related SSCs to be evaluated for LTO, as outlined in Figure 5.
2. Demonstration of the methods used to monitor and mitigate ageing of selected SSCs for the LTO period. This includes a review of existing plant maintenance programs with possible required additions or modifications, as well as a review of each selected SSC to ensure that ageing is managed properly.
3. Reviewing SSCs that were subject to time limited assumption analyses to ensure that the analyses are still valid in the extended operation period, or that ageing effects are managed. The goal of this review is to investigate whether the SSCs will function within safety margins for the LTO period. (Ibid. 6-7.)

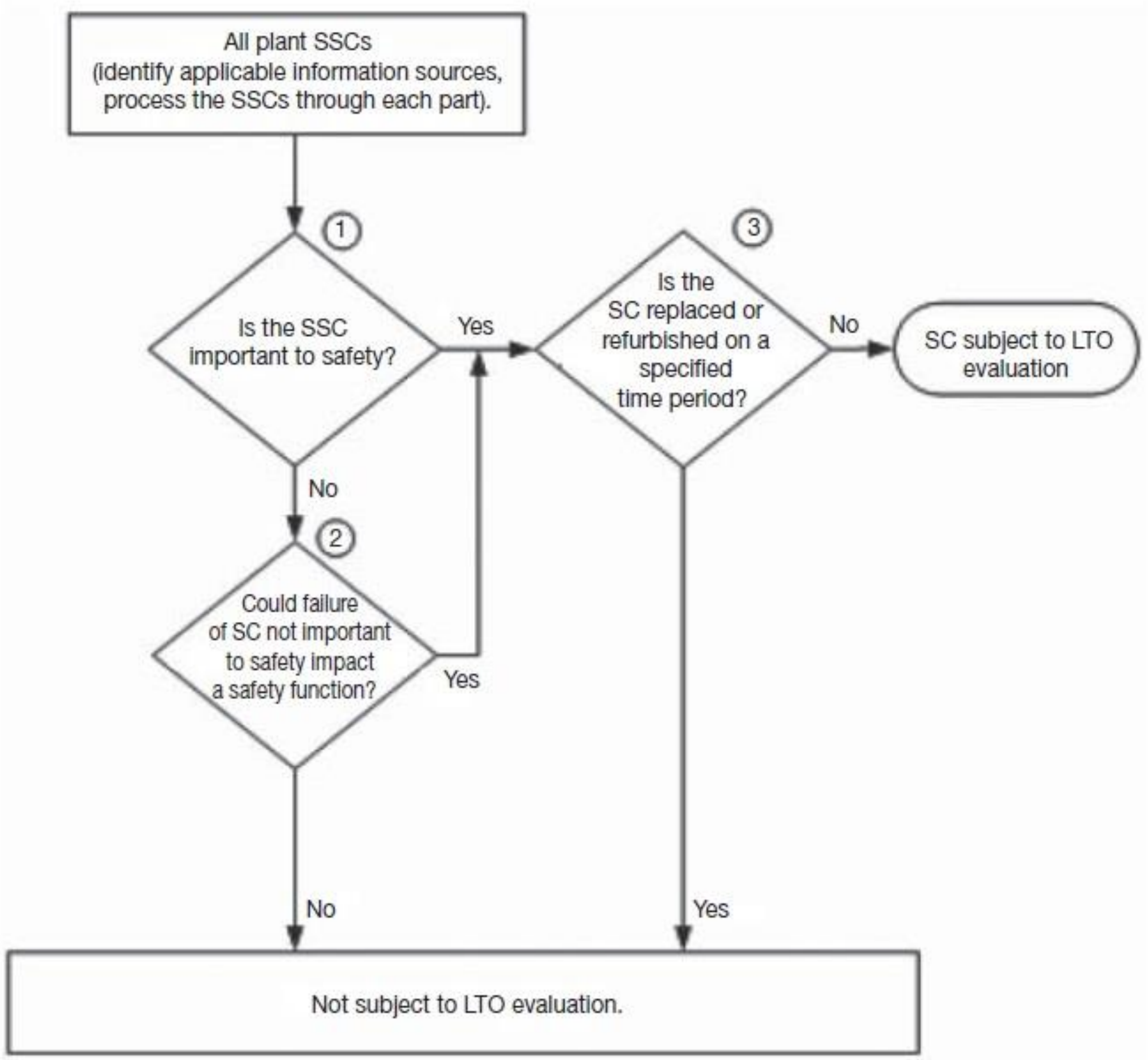

Figure 5. SSC screening process for LTO evaluation (Blaiohanu et al. 14).

Typically, SSCs that become subject to LTO evaluation are those that perform the following safety functions:

a. All SSCs important to safety measures that ensure the integrity of the reactor coolant pressure boundary.
b. All SSCs important to safety measures that ensure shut down capabilities and maintain the reactor in a safe shutdown state.
c. All SSCs important to safety measures that ensure the capability to prevent accidents that could cause off-site radiation exposure or that mitigate the consequences of such accidents. (Ibid. 13.)

There are also a number of other safety SSCs that some regulatory authorities require to be analyzed, such as ones mitigating fire, floods, extreme weather, earthquakes, pressurized thermal shocks, anticipated transients without scram or station blackout. In Finland, the licensee is responsible for listing safety SSCs (see chapter 6.1). Other SSCs that are considered in Figure 5 step 2 are ones whose failure may impact upon the operation of SSCs mentioned above. If the considered SSCs have planned replacements or refurbishments coming up, they do not need to be further evaluated for LTO. The utility may also want to assess SSCs that are not directly safety-related but are otherwise important for operation beyond the design lifetime. (Ibid.)

The process continues from the SSC screening shown in Figure 5 to a review of the current ageing mechanics, existing ageing management programs, and time limited assumptions for each SSC. If existing programs are found lacking, modifications or additions need to be made to effectively manage SSC ageing effects during the LTO period. This next phase of the process is detailed in Figure 6. (Ibid. 16.)

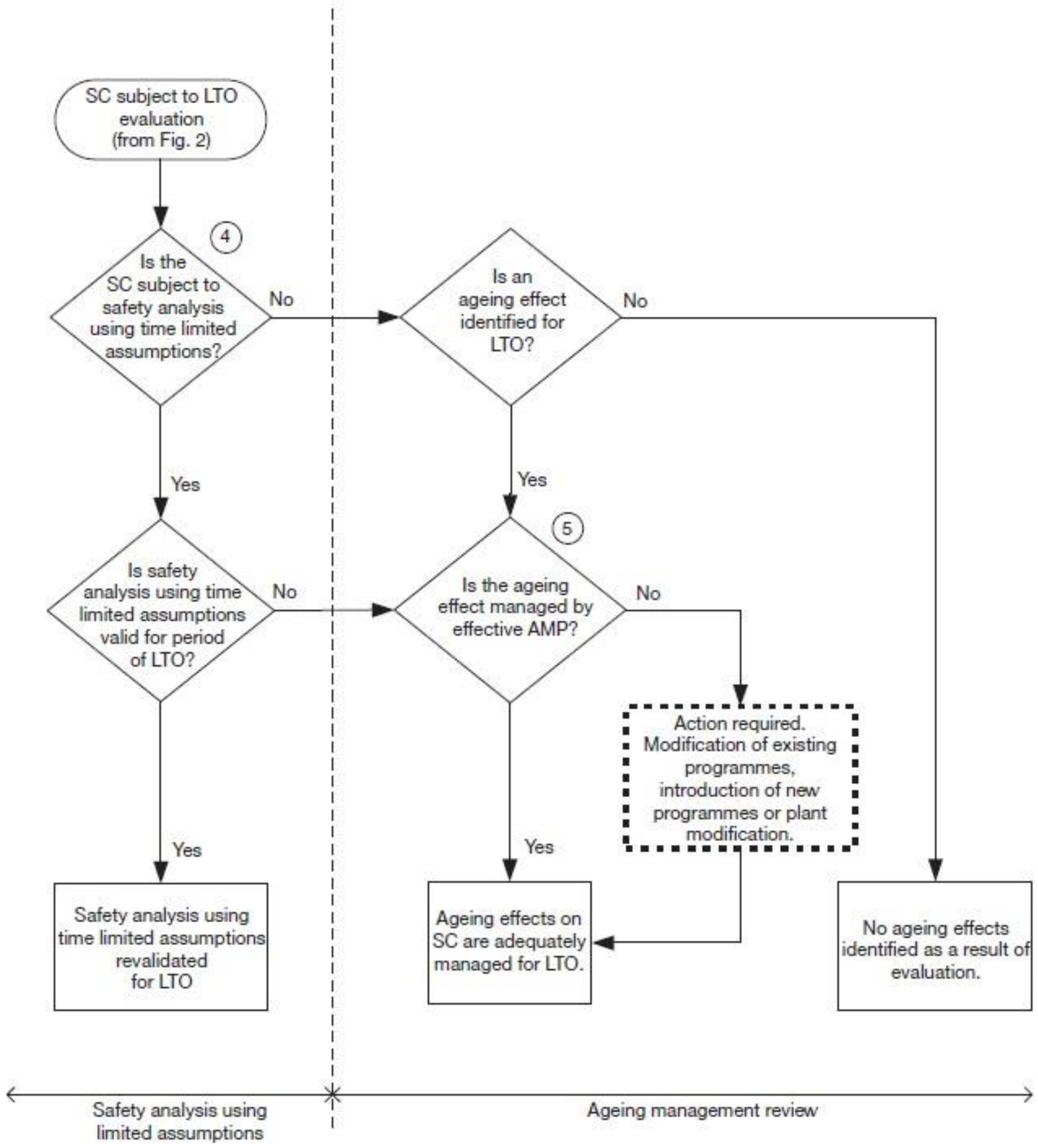

Figure 6. Review of SSC ageing mechanics, and existing ageing management programs or time limited assumptions (Blaiohanu et al. 16).

An engineering assessment is also carried out on each selected SSC. The assessment provides information on topics such as SSC design, regulations, safety analysis, material properties, and operation and maintenance history. The assessment also confirms the status of the SSCs and whether they are within the design limits or if actions are required to remedy the situation. (Ibid. 17.)

Some SSCs may have been assigned time limited assumptions, that is their safety analyses are based on an initially assumed period of operation depending on design and license terms. These SSCs need to be re-evaluated with regards to the extended operation period if their initial analysis was defined by the current operating period. The SSCs lifetimes are estimated by considering current condition, present ageing mechanisms, and acceptability of flaws discovered by in-service inspections. (Ibid. 24-25.)

Life time extension may provide a utility with decades worth of continued production and revenue, however depending on the condition of SSCs this might include sizeable investments in order to ensure operation within design limits throughout the extended period. Not only safety-related SSCs may be subject to refurbishment, as also production-related components may experience significant degradation during the design lifetime period. They should also be considered for replacement in order to ensure reliable production in the future. An important factor to consider is also the rapid evolution of nuclear regulation, as considerable modifications or additions to safety systems may be required during the normal and extended lifetime of the plant.

5.4 Problematic Projects

This chapter introduces a few examples where projects intended to increase plant lifetime or power level have instead resulted in equipment damage. In some cases, the damage has been severe enough to result in premature plant decommissioning. All cases represent the danger of unexpected events due to modifications and their consequences in the form of costs exceeding estimates, loss of production revenue, and additional investments due to mitigating or corrective actions. Conclusions that can be drawn from these examples are that large projects involving modifications require extensive planning and assessment of their impact on the rest of the power plant. Additionally, component manufacturers should not be trusted blindly with delivering excellent products. The buyer needs to be able to make sure that the product performs as is required.

5.4.1 Crystal River Unit 3

An example of a modification project gone wrong can be found from the U.S. NRC report on Crystal River Unit 3 Nuclear Power Plant (Lake et al. 2010). Crystal River had purchased new steam generators to replace their old ones. The new steam generators were to ensure extended operation beyond the plant design life. An opening had to be cut in the containment building to facilitate the replacement of the steam generators. While the opening was being created, a separation or delamination of concrete was observed in the outer containment wall alongside the opening. Since the plant was in refueling outage, the delamination did not present any immediate risk. However, it rendered the containment inoperable until fixed, so the plant could not be restarted. Investigation showed that the cause for the delamination was the scope and sequence of reinforcement tendon detensioning and cutting, which was done in preparation of the concrete cutting work. Further investigation also showed vertical cracks that had formed in the concrete around the delamination, and in several other locations around the containment wall. Essentially, the tension distribution of the concrete dome was changed so that it cracked in some locations. (Ibid. 7-8.)

Plans were made to repair the containment building, but they were eventually abandoned due to rising cost estimates. Plant modifications intended to ensure long-term operation and license renewal led to unexpected damage. The resulting repair cost estimates were high enough that the project was abandoned and the plant was permanently shut down. (Duke Energy 2013.)

5.4.2 San Onofre Units 2 & 3

Life time extension also failed at San Onofre Nuclear Generating Station in Southern California, where new steam generators experienced significant tube degradation after their first cycle of operation. The degradation was first discovered in Unit 3, where an unexpected primary-to-secondary leak was detected. The cause of the leak was identified as significant tube-to-tube wear in the free span U-bend areas of several tubes. This sort of damage was unexpected, as the steam generators had been installed only a few years before. Unit 2 was under outage at the time, and inspections concluded that similar wear was observable in its steam generators. The U.S. NRC issued a confirmatory action letter to the licensee to address the steam generator issues. (Dapas et al. 2015, 3-4.)

The licensee requested permission to operate Unit 2 at reduced power levels, but this was denied until all issues were addressed. However, neither the steam generator manufacturer nor the licensee managed to come up with a solution how to restore the steam generators to operable condition. Eventually, the licensee decided to permanently decommission the units instead of investing in further corrective measures. The licensee later issued a dispute notice to the steam generator manufacturers for a settlement as the degradation was caused by a design fault. The manufacturer had been tasked to design steam generators that could operate safely and reliably for the next 40 years. The manufacturer had also warranted that the steam generators would be free from defects for at least the next 20 years. However, the kind of tube wear that occurred was, according to the manufacturer, “unexpected and without precedent” (Mitsubishi 2015). The settlement included costs for inspections and repairs, replacement power purchases, and lost production revenue for the rest of the unit lifetimes. In 2015, settlement demands of all co-owners of the power plant reached a total of $7,57 billion. The dispute is still under arbitration by the International Chamber of Commerce. (Dapas et al. 3-4.)

6 LIFE CYCLE MANAGEMENT IN FINLAND

This chapter explores the life cycle management models used in Finnish nuclear and paper industry. The methods used by TVO are not included, as they are investigated in chapter 7. The baseline for safety-related ageing management is provided by the Finnish government in the form of the Nuclear Energy Act and government decrees. These are elaborated on by STUK in the Nuclear Power Guides (YVL-Guides). While the ageing management side is subject to regulation, the economic side of LCM is not. Therefore, utilities can use different methods to optimize their maintenance and modification strategies within the boundaries of the regulations with regards to safety-related SSCs and with risk-informed decision making with regards to the production-related SSCs.

6.1 Regulations

In Finland, the utility submits an application for operating license (or license extension) to the Ministry of Employment and the Economy, which reviews the application and presents it for approval to the government. The application cannot be approved unless a statement has been provided by STUK, ascertaining that the nuclear power plant can be operated according to the requirements of the Finnish Nuclear Energy Act. An ageing management review is integral to the license application, and it is also evaluated by STUK. (Ministry of Trade and Industry 1987.)

The Finnish government has also issued a number of decrees attaining to the use of nuclear power and radiation exposure. Government decree 717/2013 describes the safety requirements for nuclear power plants. It also sets the limits for radiation exposure for plant workers and the public. These limits serve as a basis for much of the safety engineering, as no accident scenarios can be allowed to cause radiation doses or release of radioactive material higher than the limits presented in the decree. The utility must present comprehensive plans on the prevention and mitigation of the accident scenarios when applying for a construction and operating license. On the prevention and mitigation of accidents, the decree requires the following levels of defense:

1) Such prevention systems must be in place that ensure normal operation and ensure that deviations from normal operating conditions are rare.

2) Deviations from normal conditions need to be controlled to limit development of deviations into accidents and systems must be in place that can bring the plant back into a manageable state.
3) Accident situations need to be controlled so that automatic systems are able to reliably prevent severe fuel damage. Manual systems may also be used if they can be justified from a safety perspective.
4) In severe reactor accidents, the release of radioactive substances must be confined so that they do not exceed the decreed limits.
5) Emergency arrangements must be in place to mitigate radiation exposure of the public in situations where radioactive substances are released into the environment. (Finnish Government 2013, 5-6.)

Government decree 717/2013 replaced the earlier decree of 733/2008, which in turn replaced the original government decision of 395/1991. Decree 717/2013 was replaced by STUK regulation STUK/Y/1 in 2016. This reflects the culture of continuous improvement, also mentioned in decree 717/2013 as well as in the newest regulations. (Finnish Government, 11; STUK 2016, 19.)

STUK provides extensive regulatory guidance for nuclear power plant ageing management in Finland. All nuclear power related regulations are compiled into the YVL-Guides, which specify in detail all safety requirements demanded of nuclear power utilities and derive their legitimacy from the Nuclear Energy Act.

Ageing management is discussed in YVL A.8 (STUK 2014). It describes, in detail, the requirements on countering ageing, both physical degradation and obsolescence, that are to be taken into account in the design, procurement, fabrication and operation of all safety-related SSCs. In addition, it lists the common ageing mechanisms that affect nuclear power components, specifying which materials or components are especially susceptible to each form of ageing. (Ibid. 4-7, 15-22.)

Furthermore, it specifies the need for condition monitoring and preventive maintenance. No safety-related SSC is to be deliberately run to failure. The availability of the SSCs needs to be upheld as detailed in the design basis requirements. Inspections, tests, measurements and analyses are to be used to determine the continued availability as well as the impact of operating conditions. Regular and preventive maintenance is to be conducted to avoid reduced availability. Condition monitoring and maintenance programs are to be in place for each SSC complete with timetables or maintenance intervals for the entirety of their service lives. (Ibid. 3, 7-9.)

Spare parts are to be available and operable for such SSCs that affect the safe state of the facility during prolonged transients and accidents. The spare stock must cover at least one redundant subsystem of 100 % capacity that can provide for the safe state. Any modifications made to the plant in the form of new SSCs are subject to the same requirements as SSCs part of the original plant design. (Ibid. 10-11.)

Finally, the guide specifies the requirements on the ageing management program that is to be submitted for review to STUK, as well as follow-up reports that are to be submitted annually. The reports contain information on how successful the ageing management program is, such as failure rates, major service work, ageing effects on safety margins, development needs of the program, and the spare part stock situation. (Ibid. 11-13.)

More specific SSC requirements are given in other YVL guides, which have detailed guidelines about safe design, operation and maintenance activities as well as their technical and administrative implementations, supervision and correct reporting procedures. These guides cover the safety-related SSCs; the ageing management plan must incorporate them all in a satisfactory manner in order for the power utility to obtain an approved operating license from the regulatory authority. A comprehensive list of the guides can be found in Table 2. The ones giving more specific requirements related to ageing management are marked in yellow. (Ibid. 4.)

Table 2. Complete list of YVL guides. The ones related to ageing management marked in yellow. (Based on STUK 2014, 4.)

Group A: Safety management of a nuclear facility	**Group B: Plant and system design**	**Group C: Radiation safety of a nuclear facility and environment**	**Group D: Nuclear materials and waste**	**Group E: Structures and equipment of a nuclear facility**
A.1: Regulatory oversight of safety in the use of nuclear energy	B.1: Safety design of a nuclear power plant	C.1: Structural radiation safety at a nuclear facility	D.1: Regulatory control of nuclear safeguards	E.1: Authorised inspection body and the licensees in-house inspection organisation
A.2: Site for a nuclear facility	B.2: Classification of systems, structures and components of a nuclear facility	C.2: Radiation protection and exposure monitoring of nuclear facility workers	D.2: Transport of nuclear materials and nuclear waste	E.2: Procurement and operation of nuclear fuel
A.3: Management system for a nuclear facility	B.3: Deterministic safety analyses for a nuclear power plant	C.3: Limitation and monitoring of radioactive releases from a nuclear facility	D.3: Handling and storage of nuclear fuel	E.3: Pressure vessels and piping of a nuclear facility
A.4: Organisation and personnel of a nuclear facility	B.4: Nuclear fuel and reactor	C.4: Assessment of radiation doses to the public in the vicinity of a nuclear facility	D.4: Predisposal management of low and intermediate level nuclear waste and decommissioning of a nuclear facility	E.4: Strength analyses of a nuclear power plant pressure equipment
A.5: Construction and commissioning of a nuclear facility	B.5: Reactor coolant circuit of a nuclear power plant	C.5: Emergency arrangements of a nuclear power plant	D.5: Disposal of nuclear waste	E.5: In-service inspection of nuclear facility pressure equipment with non-destructive testing methods
A.6: Conduct of operations at a nuclear power plant	B.6: Containment of a nuclear power plant	C.6: Radiation monitoring at a nuclear facility	D.6: Production of uranium and thorium	E.6: Buildings and structures of a nuclear facility
A.7: Probabilistic risk assessment and risk management of a nuclear power plant	B.7: Provisions for internal and external hazards at a nuclear facility	C.7: Radiological monitoring of the environment of a nuclear facility		E.7: Electrical and I&C equipment of a nuclear facility
A.8: Ageing management of a nuclear facility	B.8: Fire protection at a nuclear facility			E.8: Valves of a nuclear facility
A.9: Regular reporting on a nuclear facility				E.9: Pumps of a nuclear facility
A.10: Operating experience feedback of a nuclear				E.10. Emergency power supplies of a nuclear facility
A.11: Security of a nuclear facility				E.11: Hoisting and transfer equipment of a nuclear facility
A.12: Information security of a nuclear facility				E.12: Testing organizations for mechanical components and structures of a

6.2 The Fortum Process

Fortum Power and Heat Oy controls the other nuclear power plant in Finland. It has two pressurized water reactors (PWRs) and is located in Loviisa. LCM in Loviisa is centered around maintaining availability for safety and production critical SSCs, as well as economic maintenance for other SSCs whenever it can be justified. Information gathering on SSC condition and ageing effects is conducted mainly by system experts, on a system basis. Maintenance workers also provide input as they make observations while carrying out their duties. SSCs are categorized into Ageing Class and Maintenance Criticality Class. Ageing Class A includes SSCs that can limit plant lifetime and directly affect production through their unavailability, such as the RPV, main coolant pumps and steam generators. Class B SSCs are other important production- or safety-related SSCs. The rest of the SSCs are categorized into Class C, and are part of normal operation and maintenance functions. Class A and B have assigned system engineers that monitor system condition and ageing, with dedicated support persons overseeing each SSC in Class A. Ageing Class categorization is illustrated in Figure 7. (Kytömäki & Laakso 2016.)

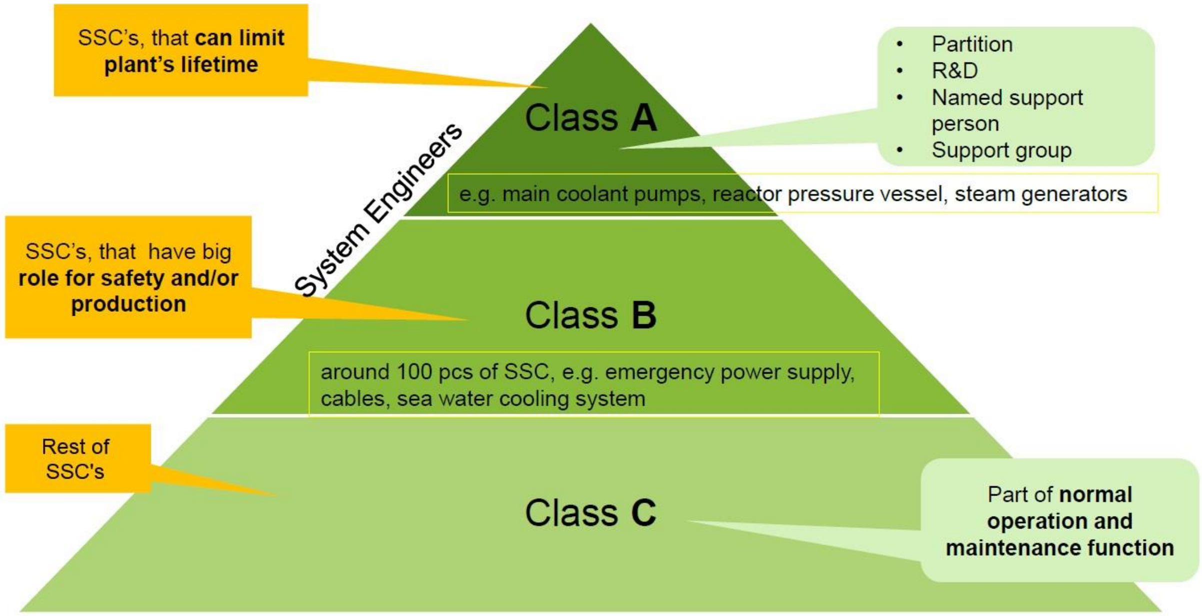

Figure 7. Fortum Ageing Class categorization (Based on Laakso 2016, 4).

Maintenance Criticality Class is determined through a series of questions, leading to a total of 4 classes, which determine the maintenance strategy used for each SSC. The selection process with its questions is shown in Figure 8.

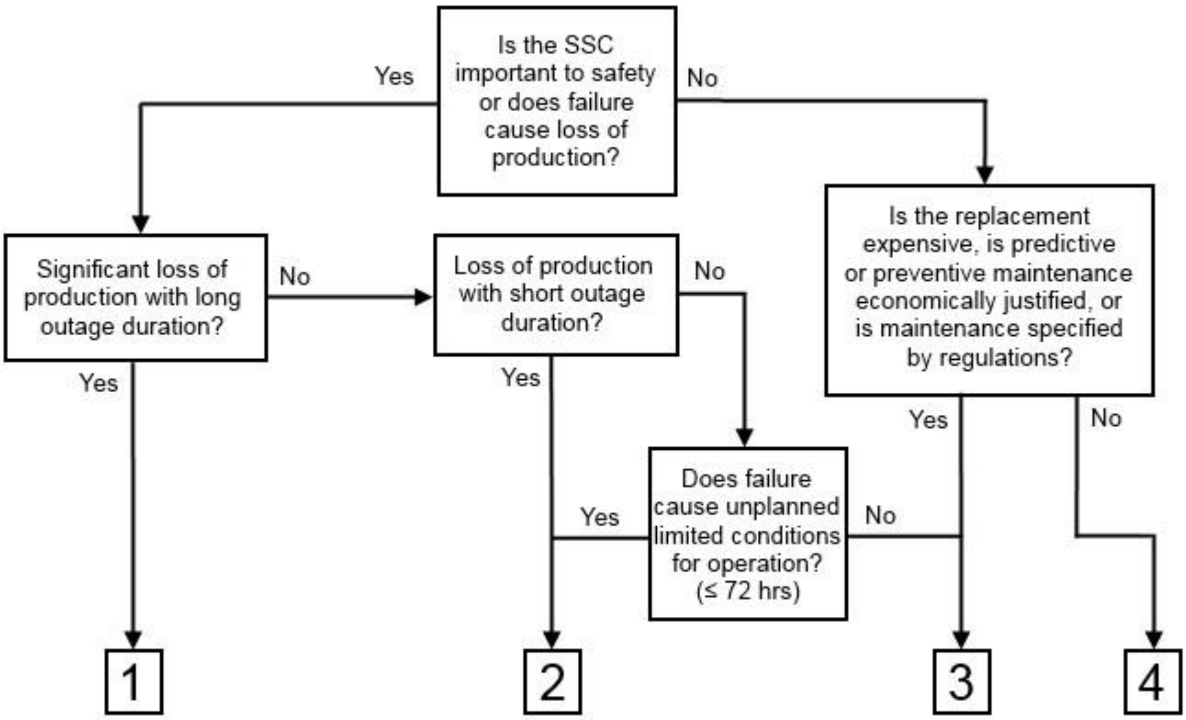

Figure 8. Fortum Maintenance Criticality Class selection process with questions. The definitions for significant loss of production, loss of production and outage durations are confidential. (Based on Kytömäki 2016.)

The main maintenance strategies are predictive and preventive maintenance. Predictive maintenance is condition based and includes online condition monitoring and surveillance, while preventive maintenance is time based and focuses on periodic inspection and maintenance. The most critical systems are afforded both condition based maintenance and periodic maintenance. Class 3 systems are given preventive or predictive maintenance if it is economically justifiable. Class 4 systems are typically run-to-failure. Operation and maintenance (O&M) experience is used to re-evaluate maintenance strategies. Maintenance strategy selection according to Criticality Class is illustrated in Figure 9. (Kytömäki & Laakso.)

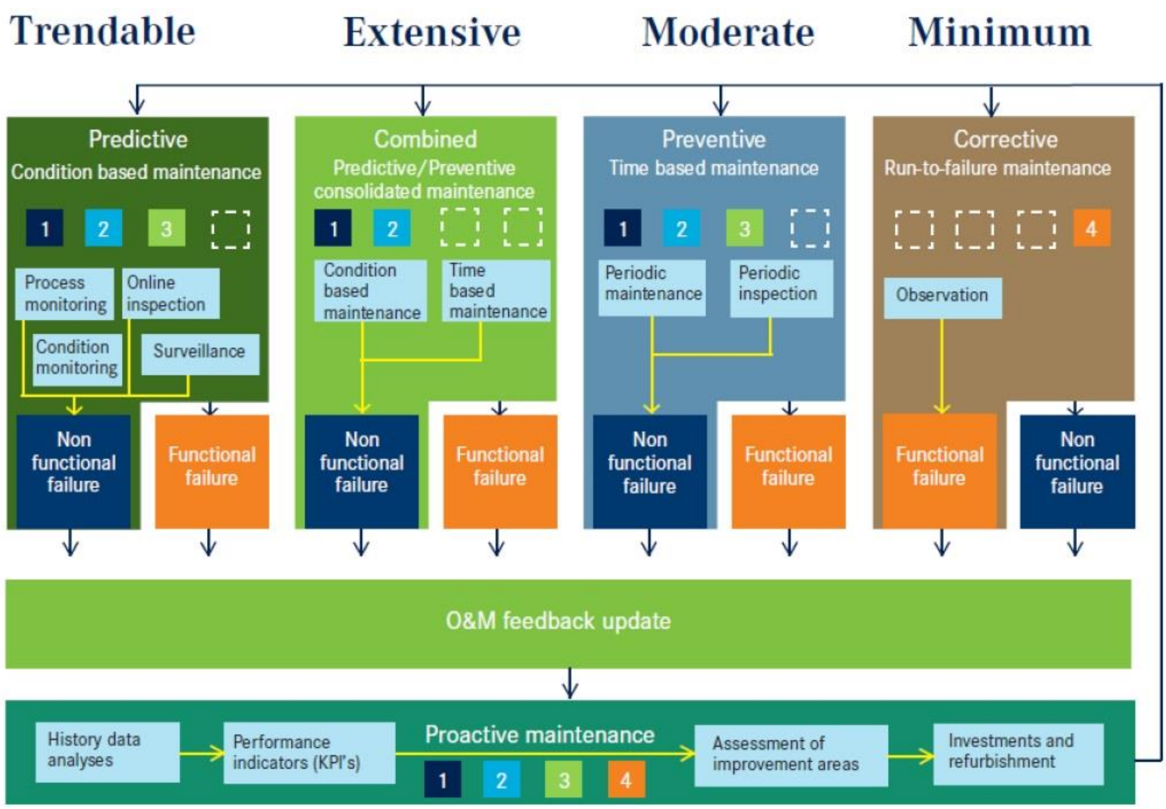

Figure 9. Fortum maintenance strategy selection according to Maintenance Criticality Class (Leino 2016, 5).

Spare part policies have seen improvement recently. SSC obsolescence is a major issue for nuclear power plants, with almost a third of the equipment being obsolete. Obsolescence management has been mainly reactive as issues are not identified until replacement spares are needed and lack of suppliers or tech support is noticed. The heavy validation and licensing process related to nuclear power reduces the amount of suppliers available. An improvement implemented in Loviisa is the introduction of a common obsolescence database, the Rolls-Royce Proactive Obsolescence Management System (POMS) database, to ease the burden of spare part engineers. Criticality Class 1 and 2 components have also been reviewed extensively to identify spare part shortages or the need for validation of new spare parts. (Kytömäki & Laakso.)

Risk analysis is used as a support tool for maintenance planning. PRA plays an important part in Criticality Class selection. Investment planning is also seeing an increase of PRA usage, evaluating production risks in addition to CDF. Some SSCs have been assigned Reliability Centered Maintenance (RCM) programs, where maintenance timing and priority is optimized with the help of risk analysis. This involves studying maintenance history and thus assessing the failure rates and effect of maintenance procedures. RCM is quite a resource-draining process, so it is typically only conducted on targets with clear potential for improved availability, safety, or cost savings. (Ibid.)

Modification projects are initiated by system experts and O&M personnel. Many smaller projects and investments are conducted independently by the O&M organization. Larger projects are introduced into a Ten Year Plan, which contains approximations on upcoming projects. Recently, a point based system has been introduced to assist in investment prioritization. Points are gained according to the assumed benefit gained to nuclear safety, production, maintenance, environmental factors, occupational hazards, etc. The benefit points are weighted by a risk factor, which assesses the impact of project risks on the attainability of the project benefits, as well as importance to company strategy. These contribute to a final investment benefit score that can be used when comparing projects and deciding on priorities. There are also plans for creating a centralized group of experts to review and prioritize project investments. (Ibid.)

When investment proposals are considered for approval, an investment analysis is first conducted. The analysis aims to find the optimal time to implement the investment. It may be implemented according to the original proposal, be postponed, or not implemented at all. The risk of postponing or not implementing the investment is assessed. Resource allocation can be problematic as there is no centralized system to track assigned resources, which fluctuate all the time. Introducing some extensive resource tracking software could improve the situation, but such applications often require specific expertise to use and can be quite expensive. A simple but effective system can be difficult to find. As the Loviisa units are approaching the end of their lifetime in the mid 2020’s, investments are considered according to their relevance to the remaining lifetime. Economic justification becomes more important as the years of remaining production become fewer. Premature decommissioning becomes possible if extensive modifications become necessary closer to the end date, especially if their importance to safety or production is high. If the plant cannot operate for the final years without an investment that would not see payback during those final years, it would be cheaper to just decommission the plant instead of implementing that investment. (Ibid.)

6.3 UPM Paper Mill Process

Life cycle management in the paper industry is motivated by economic criteria. Risks are associated with production reliability. Production depends on two factors, availability and product quality. While the industry was in top demand, paper mills were run to produce maximum yield with minimal allowed unplanned unavailability. Maintenance investments focused on preventing unplanned outages and increasing efficiency. As the demand for paper has declined, the priority criteria of maintenance investments have shifted. (Pasanen 2016.)

Due to the nature of paper production and operation of paper machines, there are recurring short outages every few weeks and two to three somewhat longer outages each year. Maintenance is planned around these outages, with smaller regular maintenance focused on the shorter outages and larger repairs and refurbishments focused on the longer outages. Paper machines also include several components that are replaced in-service, such as certain conveyor rolls. (Ibid.)

The most significant ageing mechanisms present in paper mills are corrosion, vibration fatigue, and mechanical wear. Ageing is monitored online for the more critical components and through operational maintenance procedures during operation. Operational maintenance refers to the practice of mixing operative and maintenance expertise so that operators can conduct maintenance work and maintenance personnel can take on operator tasks. As operators are familiar with the machines they operate, they can identify indicators of impending SSC failure while conducting their normal operative tasks. This leads to better knowledge of current machine condition and more efficient maintenance planning, as it augments existing condition data gathering procedures. (Ibid.)

Obsolescence replacement is also practiced, as the loss of spare part supply or technical support renders use of obsolete SSCs risky or too expensive. Performance upgrades are no longer done as the market situation of oversupply do not allow such measures. (Ibid.)

The most critical SSCs are subject to recurring, time-dependent maintenance. This type of maintenance is financed through the maintenance budget. Other components are categorized as run-to-failure, or more correctly run-to-indication, as indicators of SSC failure often present themselves rather early, so preventive maintenance can be carried out at the next suitable outage. Maintenance plans are laid according to condition data, industrial information gathering, and upcoming outages. The most efficient time for maintenance is estimated so that repair or replacement is carried out as close to SSC time of failure as possible. (Ibid.)

Investments are categorized as environmental- and safety-related, forced investments, and payback investments. Environmental and safety investments are mainly focused on emission reduction equipment, waste water treatment and occupational hazard reduction. Forced investments deal with failing equipment that must be replaced or repaired in order to continue operation. Payback investments include cases where significant economic benefit can be gained, such as replacement of aged equipment that has very high maintenance costs, or greatly influences production quality or availability. (Ibid.)

Investments are typically not optimized in any other way than through timing of spare part purchases. The turnover of spare inventory should preferably be less than a year for operational assets. Strategic assets, such as large transformers or gearboxes are typically stored for far longer periods, as procurement of such components can take up to a year, and such a long period of production unavailability is unacceptable. Reduction of spare inventory turnover is achieved through information gathering on SSC failure and the procurement timing of a spare to coincide as close as possible to the outage in which said SSC will require maintenance. The entire LCM process is outlined in Figure 10. (Ibid.)

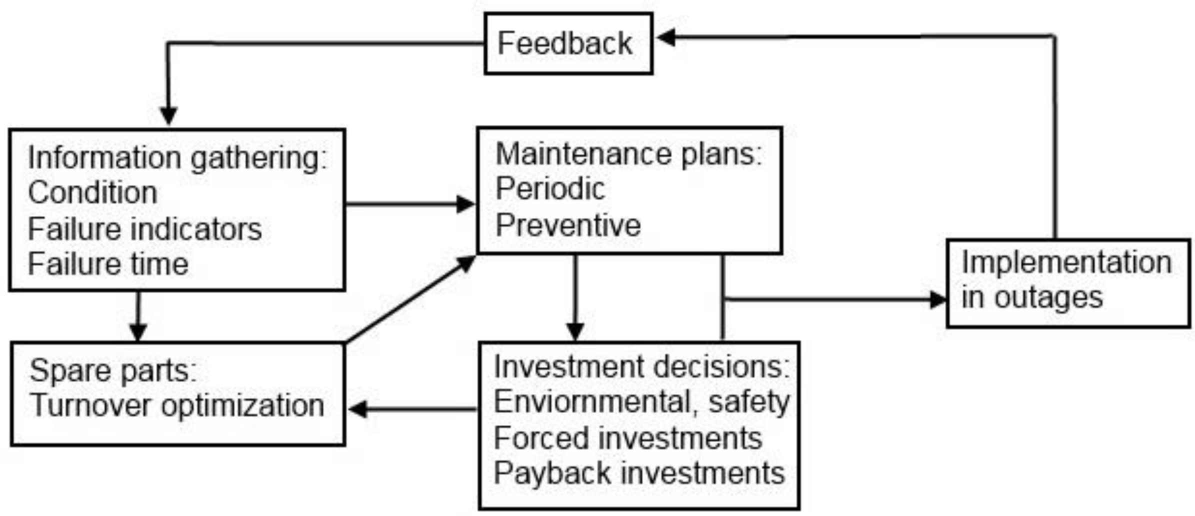

Figure 10. UPM Paper Mill LCM process.

In conclusion, the paper industry in its current market situation focuses on economic operation of its assets, with product quality and availability being the main criteria for maintenance. Critical components are maintained with regular time intervals, while other SSCs are run until indications of impending failure appear, at which point preventive maintenance is scheduled. Condition monitoring is done by utilizing operational maintenance expertise and in some cases monitoring systems. Knowledge of SSC ageing progression and failure is gathered from industrial experience. Spare part purchases are optimized to coincide as close as possible with SSC replacement. Investments are not made unless they are absolutely necessary. Investments are motivated by environmental or safety reasons (in order to follow regulations), failing equipment, or significantly increased economic benefits such as reduced maintenance and operation costs. (Ibid.)

7 THE TVO PROCESS

Management of plant ageing at TVO consists of ageing management and life cycle management. Ageing management is focused on safety-related SSCs, while life cycle management expands the process to encompass all plant SSCs. (Tauluvuori 2016, 2.)

7.1 Life Cycle Management at TVO

Life cycle management at TVO aims to uphold long-term production capability. The process analyses need for modifications and upgrades in order to reach the goals set by the company's long term vision. This is achieved with the help of operative experience from own and other facilities, knowledge of technological advancements, and by staying up to date on changes in regulations. The majority of LCM related costs are attributed to modification investments, while maintenance operates under a separate budget. (Rankonen & Salonen 2016, 68.)

The TVO LCM process begins with an information gathering phase, where data on SSC ageing is gathered. SSCs are also categorized into Safety and Maintenance Classes, according to their importance. Maintenance programs are assigned according to maintenance categorization. Annual ageing reports are also prepared and assessed, in order to identify potential for improved safety, reliability or efficiency. When need arises, modification projects are planned and investment proposals submitted. Such proposals are reviewed and prioritized in the investment planning process. Projects are annually selected into the budget and implemented. Modifications to plant functions are documented and any changes to maintenance procedures are taken into account. Information on maintenance history, changed reliability, safety and efficiency are communicated back to the information gathering phase. An illustration of the LCM process is presented in Figure 11. (Jakonen 2016, 3.)

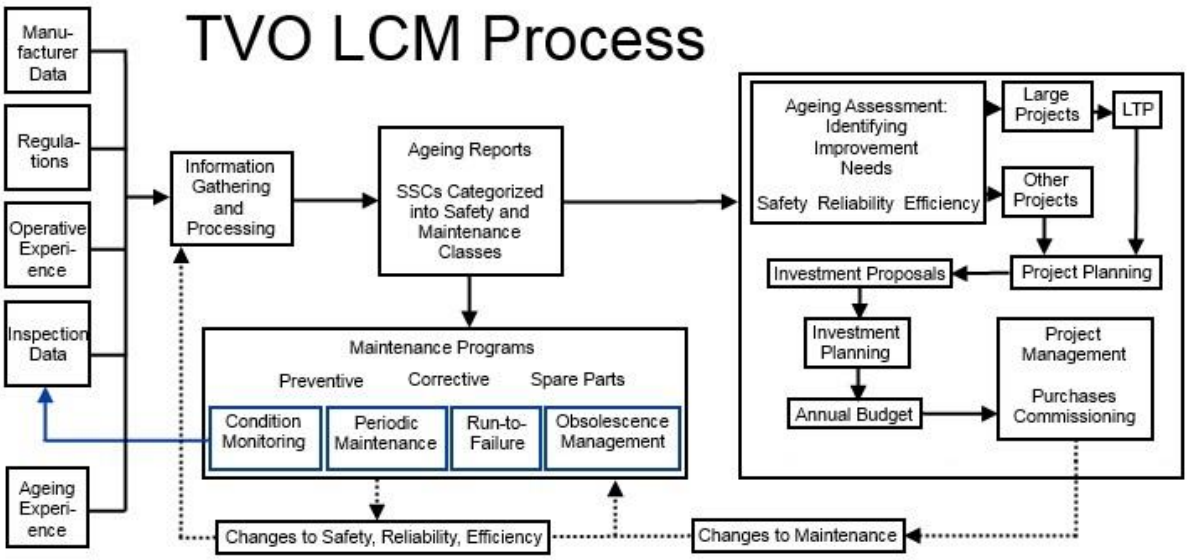

Figure 11. TVO LCM process chart (based on Jakonen, 3).

7.1.1 Organization

The LCM process is handled by the Technical Services department. An exception is the maintenance section, outlined separately in Figure 11, which is handled by the Production department. In addition to the LCM process, there are supplementary areas of responsibility, such as an Asset Manager, who systematically reviews the operation and maintenance of power plant resources, and the scope, execution and risks of upgrades in order to preserve fleet asset value, optimize lifetime and minimize production and maintenance costs. Different centers of expertise are tasked with understanding the ageing mechanics and effects concerning their area of responsibility and to coordinate corresponding ageing management actions. The Production department is responsible for ageing management through appropriate operative measures, water chemistry, and gathering of operative experience. The Production department also takes care of mitigating actions such as preventive and corrective maintenance, spare part management and maintenance history collection. Quality control is responsible for ageing analysis related to inspection results. Information transfer and division of responsibility between the departments is ensured through a series of expert task groups. Ageing management in general is overseen by the ageing management task group. (Rankonen & Salonen, 69-73; Tauluvuori 3-4.)

7.1.2 Information Gathering

The information gathering phase aims to provide knowledge on SSC condition, which is used to determine improvement needs for long term planning and project investments. The process consists of two parts: data acquisition and data processing. Data is acquired from several sources, including:

- Legal and regulatory directives.
- Company strategic goals.
- Operative experience, own and others’ (co-operation with Swedish utilities, etc.).
- Plant and SSC manufacturer guidelines and experiences.
- Research.
- Plant inspection reports.
- Ageing management task group reports and spreadsheets.
- Olkiluoto area plan.
- Device, system and unit function reports. (Jakonen, 5-6; Rankonen & Salonen, 69.)

The device, system and unit function reports are based on a system of experts designated to different areas of responsibility that gather information on and monitor the ageing effects and condition of that area. Device experts are responsible for certain types of components, system experts for certain power unit subsystems, and unit function experts for larger, system-spanning functions. There are also technical experts designated to a certain area of expertise, such as electrical, structural or automation. Device and technical experts periodically report on the status of their designated areas to the system experts. (Härmälä 2016, 5-6)

System experts analyze if a system has been operating as designed, if operating margins are sufficient and whether there are factors that may contribute to system unavailability in certain operating modes. They report annually on the status of their respective systems. The system report includes information on:

- The most significant system observations, gathered from the device expert reports.
- System operative experience, as well as the most significant system experience from other facilities.
- The most significant system technical events and observations, as well as implemented and upcoming changes and modifications.

- Recognized ageing mechanisms affecting the system and their status.
- Changes made to system design basis.
- Updates to regulations and documents concerning the system. (Ibid. 7-8.)

On the basis of the information included in the report, the system expert gives a statement on the system's compliance with its design basis and regulations, whether there is a risk of reduced safety or operating margins, and whether the current ageing trend will endanger system functions during the remaining plant lifetime. The system expert also presents the planned and required short and long term structural changes and improvement needs of the system. System experts update their respective system's information into an ageing assessment spreadsheet. The spreadsheet displays data on system condition, both physical and technological, as well as operative experience. The system experts also estimate system risk level based on failure probability and consequence. An example of the ageing spreadsheet is presented in Table 3. (Ibid.)

Table 3. TVO Ageing Assessment Spreadsheet.

		Ageing					Risk		
System Number	System name	Physical	Technological	Operative Experience	Reasons for ageing (if 3 or 4)	Suggestions for mitigation, information on ongoing projects	Failure Probability	Failure Consequence	Risk Level
100	System A	2	1	1			5	6	
101	System B	2	2	4			5	5	
102	System C	3	2	2			6	6	
103	System D	2	2	2			5	7	
104	System E	4	4	3			7	7	
105	System F	2	2	2			5	6	

Physical condition ranges from 1-4, with a score of 1 given to a system in excellent or as good as new condition, while 4 indicates that a system needs renewal and has a limited remaining lifetime. Technological condition index 1 is given to systems that boast the latest technology, while complete loss of tech support, difficulties acquiring spare parts or inability to fulfill requirements result in an index of 4. Operative experience index 1 is given to systems that operate normally and are subject to normal preventive maintenance. The index rises to 2 if failures begin to occur, 3 if maintenance measures are enhanced, and 4 if failures are recurring and the failure probability trend rises. Failure probability gets values between 5 and 7, with 5 indicating that failure will not happen for at least the next 10 years, 6 that failure will happen between 5 to 10 years from now, and 7 that the system will fail within the next 5 years. Failure consequences are seen from an economic point of view, with a score of 5 indicating no significant consequences, a score of 6 indicating halted production and 7 indicating outages longer than 5 days.

The unit function experts analyze if a unit function has operated according to design basis, if the design basis is accurate, if the unit function operating margins are sufficient for the functioning of the plant and whether there are factors that endanger the availability of the unit function in certain operating modes. The main purpose of the analysis is to explore improvement needs, planned structural changes and technical advances related to the unit function. The unit function experts annually report on the status of their respective unit functions. The report includes information on (Ibid. 8-9):

- The most significant unit function observations, gathered from system expert reports.
- The most significant implemented structural changes affecting the unit function.
- Changes to unit function design basis.
- The expediency of the most significant periodic inspection measures of systems related to the unit function, with regards to the design basis and regulations.
- Changes to regulations concerning the unit function.

On the basis of the information included in the report, the unit function expert gives a statement on the unit function's compliance with design basis, if the safety or operating margins have been reduced, if the current ageing trend endangers the unit function during the remaining plant life, and whether current periodic inspections produce sufficient information to determine unit function reliability. The unit function expert also presents any planned and required short and long term modifications and improvement needs of the unit function. (Ibid.)

The data produced by the unit function experts is processed into an annual report, which details the unit function specific failure reports, operating limitations and production losses, the total number of failures that cause loss of production, and the nature of those failures. The report is used to determine the fulfilment of design basis, as well as to identify improvement needs. (Ibid.)

7.1.3 Project and Maintenance Planning

The ageing management task group compiles a spreadsheet of the possible modifications or other significant measures for the next ten years. This life cycle spreadsheet is reviewed annually and updated as necessary. The spreadsheet is delivered to system experts, who together with the corresponding chief engineer review and update as necessary for their respective areas of expertise. Technical centers of expertise are responsible for administering the spreadsheet and seeing to it that projects are progressed in a timely fashion to the investment plan and to the project planning phase. (Tauluvuori, 5-7.)

The TVO Long Term Plan (LTP) for plant modifications is the main tool for upholding and improving plant reliability. It is used to ensure safe and reliable operation, as well as Olkiluoto area development according to the company strategy. Its goals are to find the right projects to ensure that company targets are achieved and resources are utilized efficiently. The LTP is divided into four parts: plant modifications, infrastructure, information systems, and other projects including baseload. Baseload projects include small investments that do not necessarily need to be specified. Projects related to life cycle management generally fall into the plant modifications or other projects category. All large projects that have significant impact on cost or power unit operation or are technically demanding are included in the LTP. All projects entered into the LTP are not necessarily implemented. On the other hand, new projects may enter the LTP relatively quickly, if unexpected failure indicators are detected. A good LCM program aims to minimize the amounts of quick LTP entries by ensuring indicators are found in time so that proper planning can take place. (Palomäki 2010, 3-6; Rankonen & Salonen, 69.)

Larger projects in the LTP are subject to a preliminary study. The study explores different implementation scenarios and gives a preliminary analysis on costs, time tables and resource allocation. All projects in the LTP require a preliminary planning phase, in which a basic project plan is formed. Different technical alternatives are compared and one of them is submitted as the investment proposal. Annual budget planning takes into its investment budget those projects of the LTP that are due for project approval during the current budget year. (Palomäki, 9; Rankonen & Salonen, 69-71.)

Components are categorized according to their Maintenance Class, which indicates how intensive maintenance is required. Components are screened and selected according to the significance of their failure upon systems and the power unit. A component's safety significance is estimated by calculating its CDF contribution through PRA. Reliability and maintenance costs are also considered. Maintenance Class defines the amount of allowed unavailability and thus the amount of required preventive maintenance, corrective maintenance, or condition monitoring. Monitoring can be either periodic or continuous. The process for Maintenance Class selection is illustrated in Figure 12. Safety-related components have a further categorization into Safety Classes. (Vaaheranta & Tauluvuori 2016, 8, 17.)

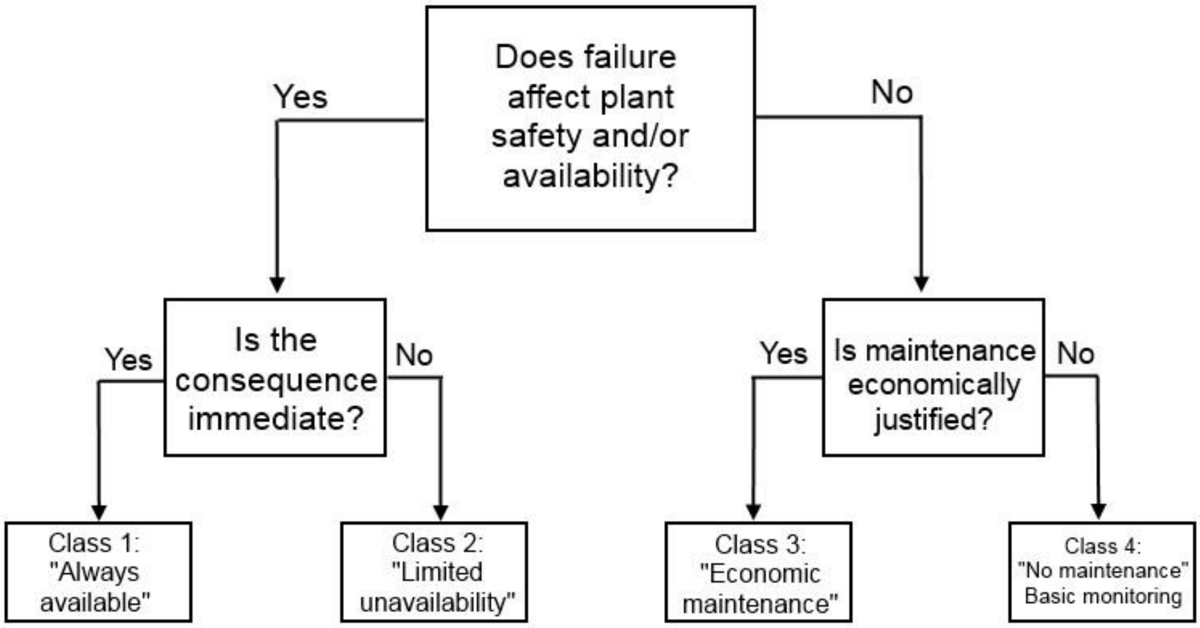

Figure 12. TVO process for determining component Maintenance Class (based on Vaaheranta & Tauluvuori, 8).

The Production department manages all routine maintenance procedures at the power units. Maintenance programs are made according to manufacturer specifications on periodic inspection and maintenance needs for associated SSCs. For the most part, maintenance is preventive and periodic. Corrective maintenance is carried out due to unexpected failures or for less important, easily replaced SSCs. Operative experience, regulations and standards also influence maintenance programs. All maintenance planning is closely related to outage planning. Some maintenance can be carried out during operation, if it does not interfere with operation or safety equipment and can otherwise be safely executed. If it cannot, maintenance is planned to coincide with outages. If the SSC is part of regulatory control, any inspection, maintenance or modification work needs to be approved by the regulatory authority. Spare parts need to have the same level of regulatory approval as the original parts that are being replaced. (Ibid. 31-33.)

Outages are performed in cycles, where typically one unit is subjected to a refueling outage (7 days) and the other to a maintenance outage (14 days). The outages are scheduled back-to-back, typically with a few days in between as a buffer for delays. The outage types alternate annually between units 1 and 2. During refueling outages, the critical time table is refueling of the reactor. Any maintenance or modification work carried out has to be completed in that time. During maintenance outages, the longest maintenance or modification project determines the critical time table, within the boundaries of the maximum outage length. Refueling is also carried out during maintenance outages. Longer outages are scheduled for when larger projects need undertaking. Outages are planned several years beforehand, together with project and maintenance planning. Action plans are also laid in place for unexpected outages in order to restore the unit to safe, operable condition as quickly as possible. (Ibid. 34-35.)

7.1.4 Investment Planning

Project investments are divided into three groups: Operative investments, production cost investments and other project investments. Operative investments include yearly recurring small acquisitions that cannot necessarily be specified, other than some tool and equipment acquisitions and spare part purchases. Production cost investments are significant undertakings that cannot be divided onto the project period but instead are recorded as annual expenses. Depending on the scale of the investment, they are either approved by the Operative Group or the Executive Board. Smaller production cost investments are approved together with the annual budget decisions. Other project investments are approved in different organizations depending on the scale of the project. The different organizations and amounts are presented in Figure 13. Managers can approve projects with investments below 50 000 €, the modification team meetings up to 100 000 €, and the TVO Management Group up to 1 000 000 €, if the projects have been entered into the annual budget. Projects that have not been budgeted can be approved by the Management Group for up to 600 000 €, after which only the Executive Board can approve them. (Palomäki. 12-13.)

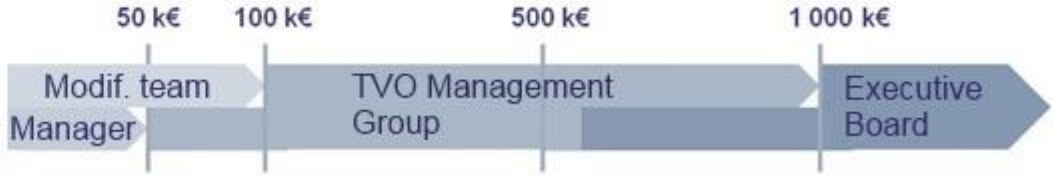

Figure 13. Project investment decision making organizations for other projects at TVO (Palomäki, 13).

Modification investments are planned and approved on a yearly basis into the annual budget. New investment proposals are received from the unit function experts as they review the status of their respective unit functions and search for improvement needs. In addition, there is a system for Action Propositions, proposals for modifications or improvements that can be submitted by anyone. If they result in smaller projects, they can be directly implemented as part of the other project investments. The information flow of the investment proposal and decision making process is illustrated in Figure 14.

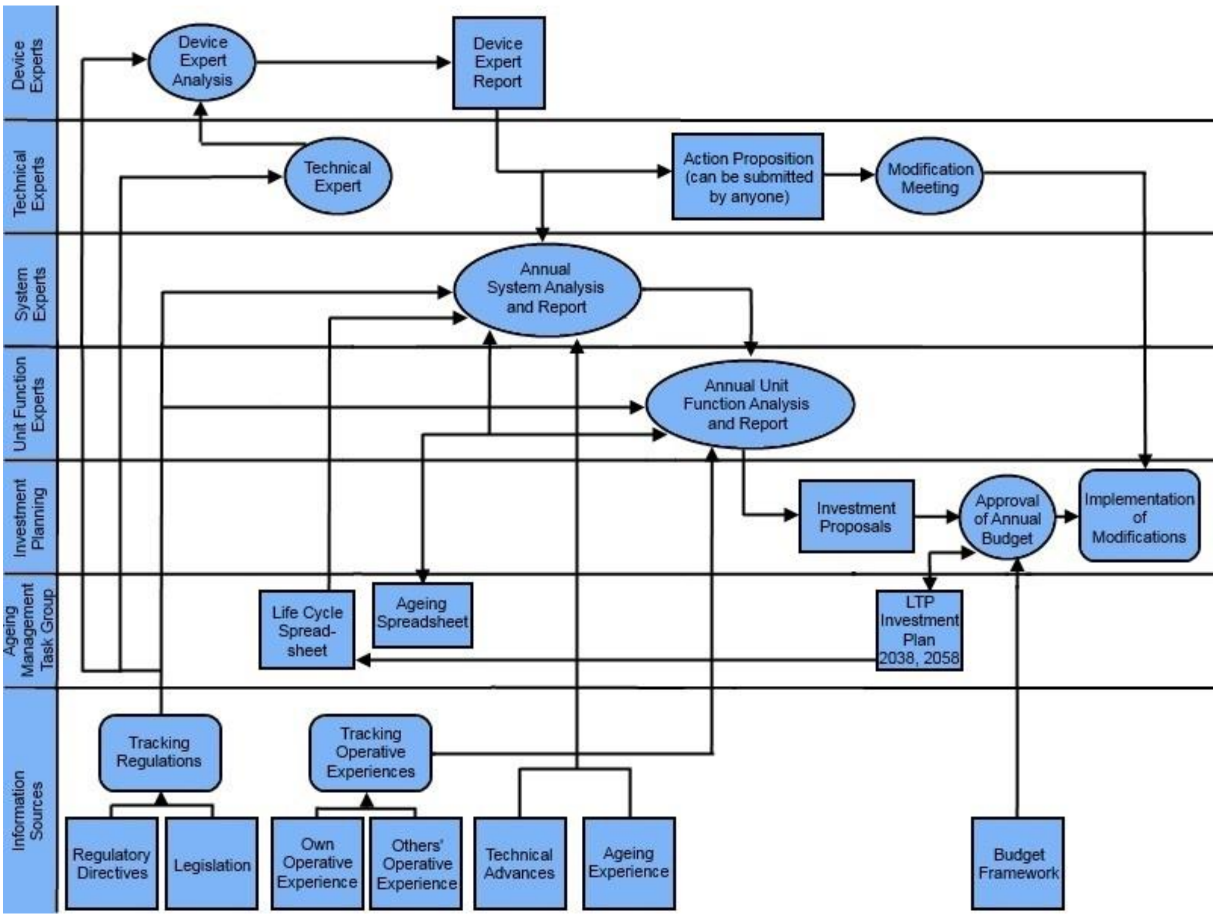

Figure 14. TVO investment process information flow chart (based on Vaaheranta 2016).

7.1.5 Problems with the Current Process

There are certain problems with the current LCM process, as it does not operate entirely as outlined in the action plans and directions referenced above. The main problems are centered around the information flow from data source to investment decisions. The problems are illustrated in Figure 15.

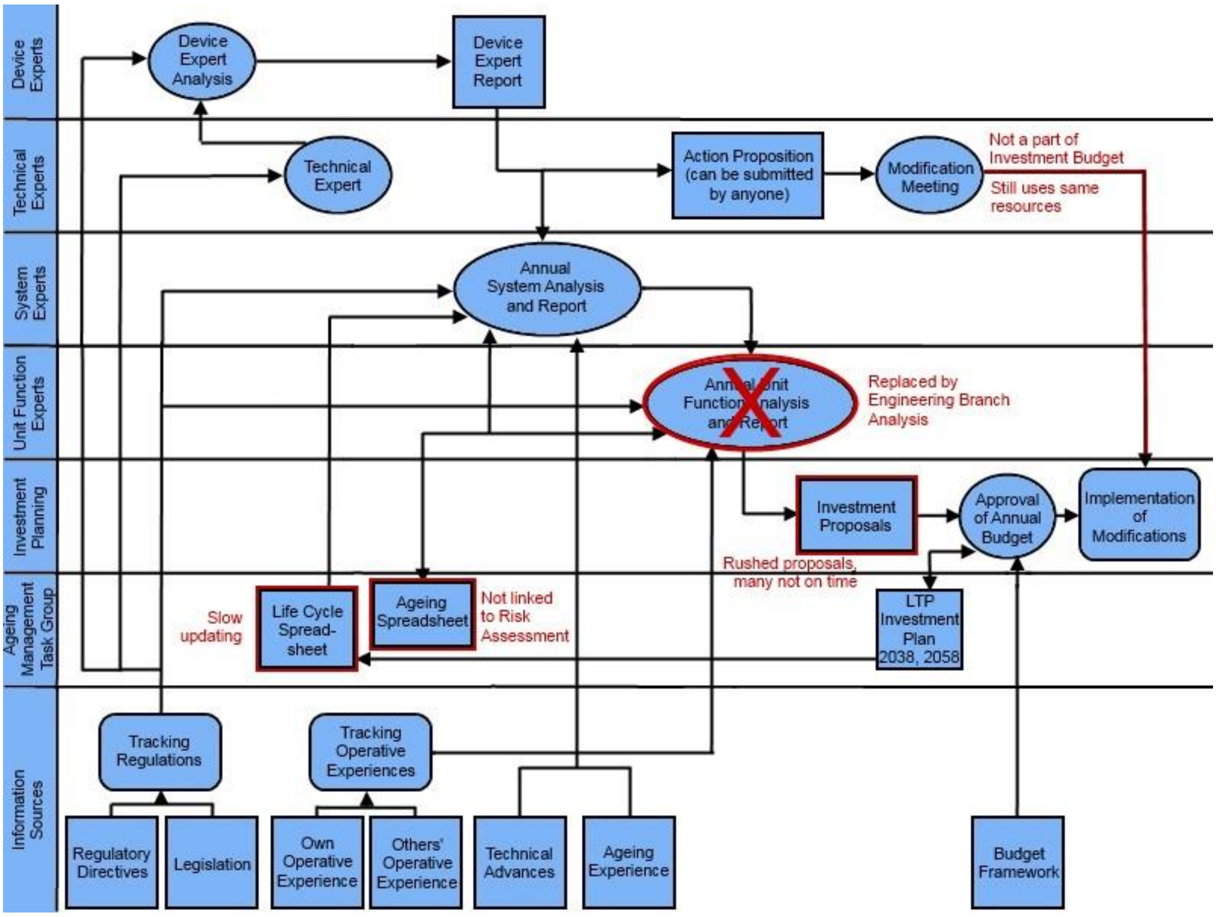

Figure 15. Problems of the investment process information flow (based on Vaaheranta).

The unit function experts, who should provide reports on the status of system-spanning functions, are not reporting annually as expected. In reality, the last time any unit function report was received was 7 years ago. System experts are instead relied upon to provide investment proposals for the annual budget. A preprocessing of the investment proposals is made by analyzing them by engineering branch, before they are presented to the annual budget meeting. The engineering branch analysis has replaced the unit function analysis to some extent, but many system experts still struggle to deliver investment proposals on time for the annual budget approval. This results in sub-optimal investment planning. (Vaaheranta.)

The Action Propositions system is also somewhat problematic. While it can help to identify pressing issues, the propositions can also completely bypass the annual budget approval phase as they are financed by other sources. This is a problem as they result in work orders that draw from the same resource pool as modification work, reducing the available manpower. (Ibid.)

The system of spreadsheets is informative, but currently not connected. The life cycle spreadsheet provides only cursory information on coming projects and there is no way to see the required cost or resource total for each outage, as projects add up. It is also updated very slowly, and no unexpected projects make it into the spreadsheet. The ageing spreadsheet is good for identifying system condition and risk, but the risk score system is not currently associated with the Risk Assessment department and their methods. Risk scores are therefore not comparable. (Ibid.)

7.2 License Renewal

The Olkiluoto reactor units were initially granted licenses for 10 years at a time since the startup of the plant in 1978. Due to the Chernobyl accident in 1986, consideration of design basis severe accidents had changed, and thus the regulatory requirements for severe accident control. Earlier, the most severe accident considered had been a large loss of coolant accident. After Chernobyl also reactor core meltdown, severe reactor pressure vessel damage and loss of containment integrity had to be considered. As the definitions for severe accidents changed, the requirements for equipment to withstand operating conditions also changed. Now, equipment had to withstand higher temperature and pressure. These requirements constituted the major modifications related to continued license approval after the first license period in 1988. (Koski 2016.)

During the first license period, a smaller reactor power uprate was conducted, raising reactor thermal power by 8 %. Another power uprate was conducted during the second license period, raising the thermal power by a further 16 %, changing the thermal power from an initial 2000 MW_{th} to a total of 2500 MW_{th}. It had to be ensured that safety systems were able to perform their function even though the reactor power had changed. These included some modifications that were to be completed before the next license renewal in 1998. In addition, STUK required that the reactors had to be able to be shut down safely in case of a deviation from normal operating conditions in case of scram failure. This requirement was met by modifying the existing emergency boron injection system. (Ibid.)

The license was renewed in 1998 for the third license period, which was now set to 20 years. However, there was to be a safety review after 10 years. The safety review did not reveal the need for any significant modifications, but the importance of equipment life time analysis was noted, especially for electrical equipment. Life time testing was originally done by artificially ageing the equipment, but documentation of these tests was lacking, so it had to be procured from manufacturers. The documentation was needed to ensure that the equipment could function in accident conditions over the scope of its design life time. (Ibid.)

The next license renewal is coming up in 2018, and preparatory work has begun. The major requirements for license renewal are related to post-Fukushima changes to regulations. For example, dependence on power supply and sea water cooling has to be reduced. There are several ongoing projects to meet the requirements, such as installing a steam powered cooling system that is powered by the reactor’s own steam. (Ibid.)

The main requirements are gained from the YVL-Guides, which were initially published in the 1970’s. The guides have been updated regularly, the most significant new requirements coming after the major accidents such as Chernobyl and Fukushima. In 2014, the guides underwent a complete remake, in order to make them clearer and more organized. After the remake, STUK required the utilities to go through the new guides and check that each requirement was met. If a requirement was not met, a plan for rectifying the situation had to be submitted, or a plea for exemption could be made. Exemptions could be granted in such cases where old plants could not in any reasonable way meet with new requirements given after they were constructed. One example is the ability to withstand a passenger plane crash (aftermath of World Trade Center), which is required of new NPPs but from which Olkiluoto 1 and 2 were exempted. (Ibid.)

The guides are somewhat flexible in the way how requirements are met by allowing for alternative solutions as long as the end result is the same. This was not the case for the government decrees on nuclear power, which were legally binding. The government decrees were converted to STUK regulations in 2016. This way, the government would not have to account for the technical demands of a very specific and complex industry, when there is an existing organization with sufficient expertise to do so. This transition allows STUK to publish legally binding regulations in addition to their guidelines. A timeline of events related to the lifetime of the TVO power plant so far is shown in Figure 16. (Ibid.)

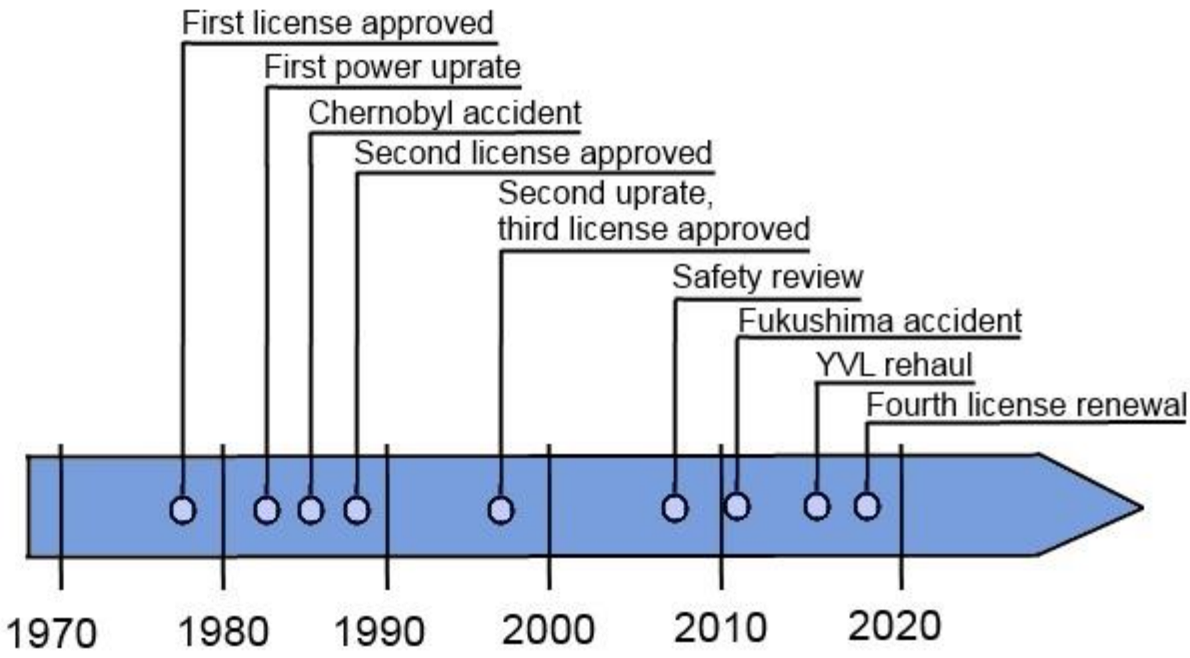

Figure 16. Timeline of events relating to license renewal and evolution of regulations (based on Koski).

One significant issue when considering license renewal is related to technological progress. As analogue equipment gives way to programmable, digital automation, the old requirements on testing make the process problematic. Each signal combination has to be tested, but digital automation has several times the number of combinations when compared to analogue equipment. This has slowed the progress on several projects involving digital automation, such as the construction of Olkiluoto 3. If the conditions for license renewal include digitalization of automation systems, this may incur significant modification needs and investments. (Ibid.)

7.2.1 Issues Related to Power Level Increase

During the first and second license periods, the power of both reactors was uprated, so that in the end both reactors had their thermal power increased by 500 MW_{th}. During the second uprate, this involved replacing the old moderator tank lid and steam separator assembly with a new, slightly higher one. As a result, the emergency cooling system pipe ends inside the reactor vessel became located in such a position, that they were hit by cold water coming in from the feed water spargers. The cold water flow alternated with hot, saturated water flowing down from the steam separators. This caused an alternating heat load upon the upper parts of the pipes, which resulted in thermal fatigue and cracking after only one cycle of operation. The upper pipe parts had to be replaced and temporary heat shields added to mitigate the thermal vibrations. A few years later the feed water spargers were replaced and the new ones installed in such a way that cold feed water would not hit the emergency cooling pipe ends. (Koski.)

The problem was mainly miscommunication between utility and manufacturer. The manufacturer had not anticipated the cold water hitting the pipes directly, as they had not been aware that the sparger discharge holes at the location of the safety system piping had been blanketed in the original sparger design. Documentation of this setup was lacking, as it was not an original design feature, but had been implemented after the design phase. This is another example of problems arising from lacking documentation and communication between manufacturer and utility. (Ibid.)

7.3 Future Scenarios

This chapter considers the possible implications of the future for nuclear power. With renewable energy on the rise and fossil-fueled power rapidly being decommissioned in Finland, the energy palette will undoubtedly look quite different in 10-15 years. These changes can be seen both as challenges and opportunities, from a nuclear power LCM point of view.

7.3.1 Energy System Transition

One important thing to consider when evaluating the remaining life of units 1 & 2 of Olkiluoto NPP is the development of the Finnish energy system and its impact on the electricity market. The development of the Finnish energy system is mainly driven by the National Climate and Energy Strategy (Ministry of Employment and the Economy 2013). The long term goal is to achieve a carbon neutral society by 2050. By 2020, the goal is to decrease greenhouse gas emissions by 20 % (compared to 1990), increase end use energy production from renewable sources to 38 %, increase biofuel share in traffic consumption to 20 %, as well as increase energy efficiency, reduce end consumption and increase self-sufficiency in electricity procurement. Much of this is achieved through economic incentives, such as subsidized production for renewable energy sources. (Ibid. 12-14, 48.)

An analysis conducted by Finnish experts (Pöyry 2015) estimates the development of generation capacity, production methods and electricity prices up to 2030 in Finland. Currently, electricity generating capacity is insufficient to meet peak demand and as such, Finland depends on imported electricity during peak load hours. Peak demand is centered around the coldest winter days. The imported power ranges around 2700-3000 MW. An example of produced and imported electricity during a day when peak demand is achieved is presented in Figure 17. (Ibid. 15-16.)

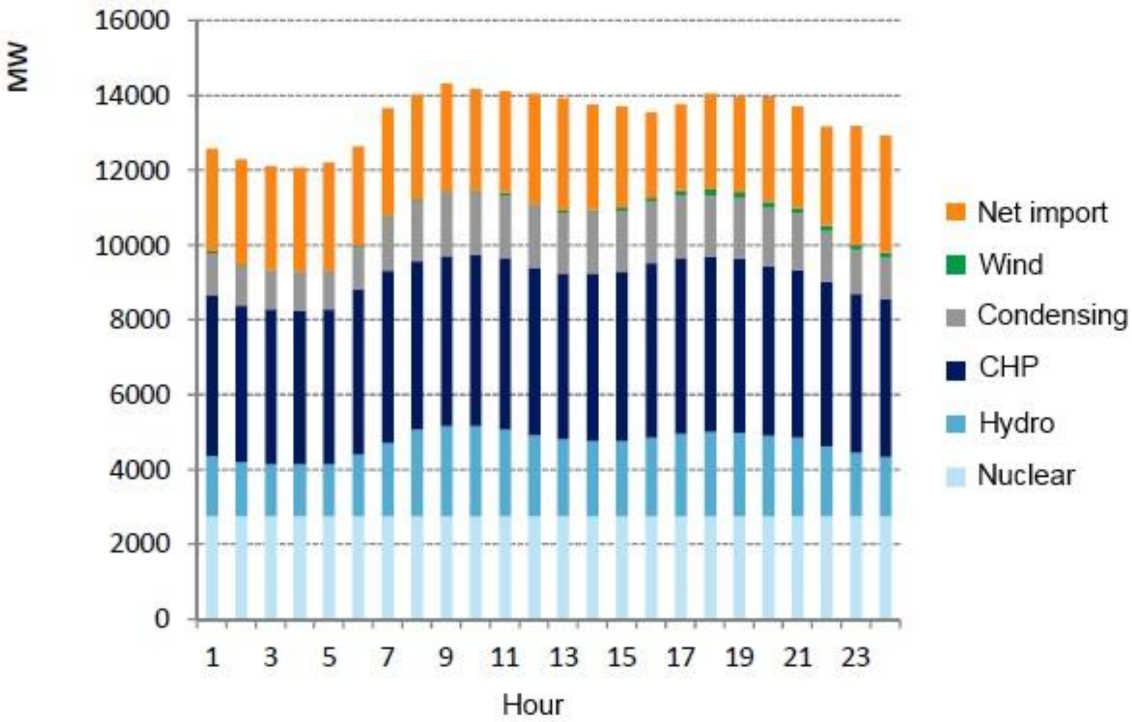

Figure 17. Electricity production by source during a peak demand day, January 2014. (Pöyry 2015, 16.)

Electricity consumption is not expected to increase significantly, as it is mainly dependent on changes in industry demand. Due to the ongoing economic downturn, only the most optimistic scenarios of economic resurgence and growth predict industrial growth and increased demand, and even in that case it would not be more than 10 TWh/a by 2030, to a maximum demand of about 95 TWh/a due to energy efficiency measures. (Ibid. 10.)

Electricity price development largely affects investments made into generation capacity. Market prices are driven mainly by the evolution of demand, fuel and emission prices, as well as the construction of new transfer links from the Nordic and Baltic countries to the rest of

Europe and the United Kingdom. Market price is based on variable production costs for current and upcoming capacity. Upcoming capacity is mainly renewable capacity, driven by subsidies. Currently, electricity prices have steadily declined as thermal coal and emission allowances plummet and subsidized renewable capacity is installed. The price trend so far is shown in Figure 18. (Ibid. 8.)

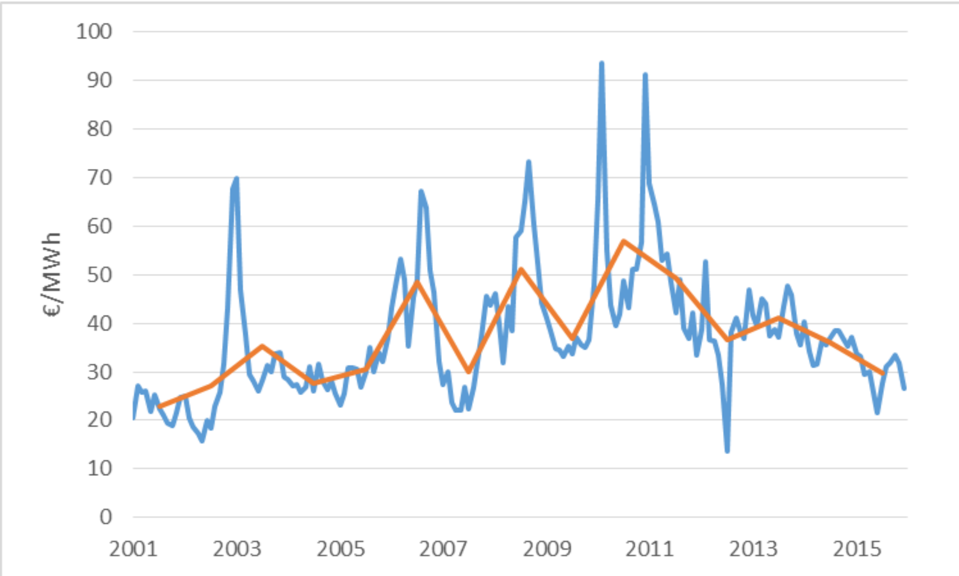

Figure 18. Electricity price development in Finland 2001-2016. Monthly average in blue and yearly average in orange. (Nordpool Spot Market Price.)

The experts' analysis includes three scenarios on how the market situation will change in the future. In the base case, the economy is gradually rejuvenated, with an increase of electricity prices that is quite significant when compared to current forward market prices (Nasdaq OMX 2016). In the slow growth scenario, the global and European economy grows more slowly, with electricity consumption and industrial production remaining at current levels. Fuel, emission and electricity prices remain low. In the fast growth scenario, the regression is quickly overcome and Europe rises into an economic upturn. New industry is founded in Finland. Energy efficiency is improved. Fuel and emission prices rise, and as a result also electricity prices will be high. The estimated evolution of electricity market prices of all three scenarios is shown in Figure 19. (Pöyry, 5.)

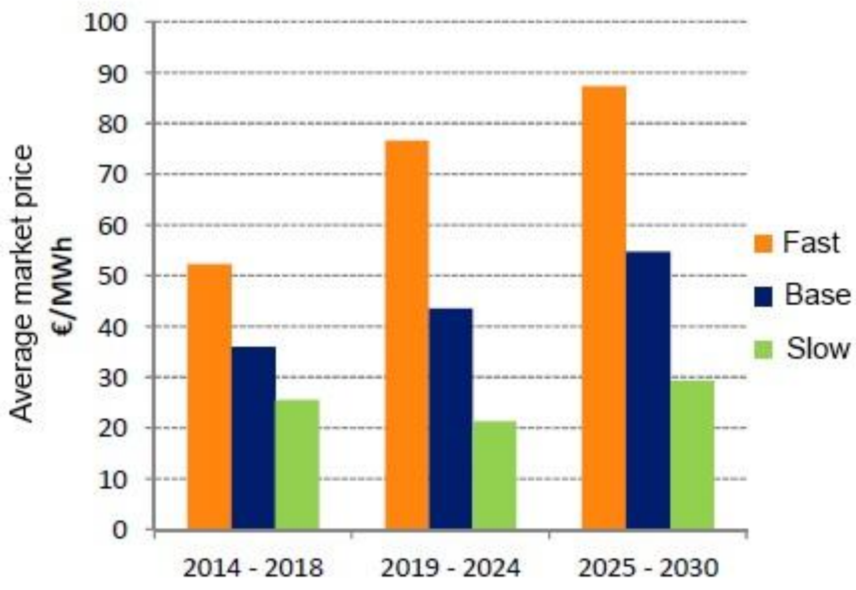

Figure 19. Evolution of electricity market prices in Finland, up to 2030. (Pöyry, 9.)

The evolution in Figure 19 is based on the assumption that fuel prices are expected to rise in the future. However, the electricity forward market is currently trading at a significantly lower price level, leading to a more moderate growth curve for electricity market prices. In Figure 20, the Nasdaq forward closing prices from April 7th, 2016 for the next 10 years is presented.

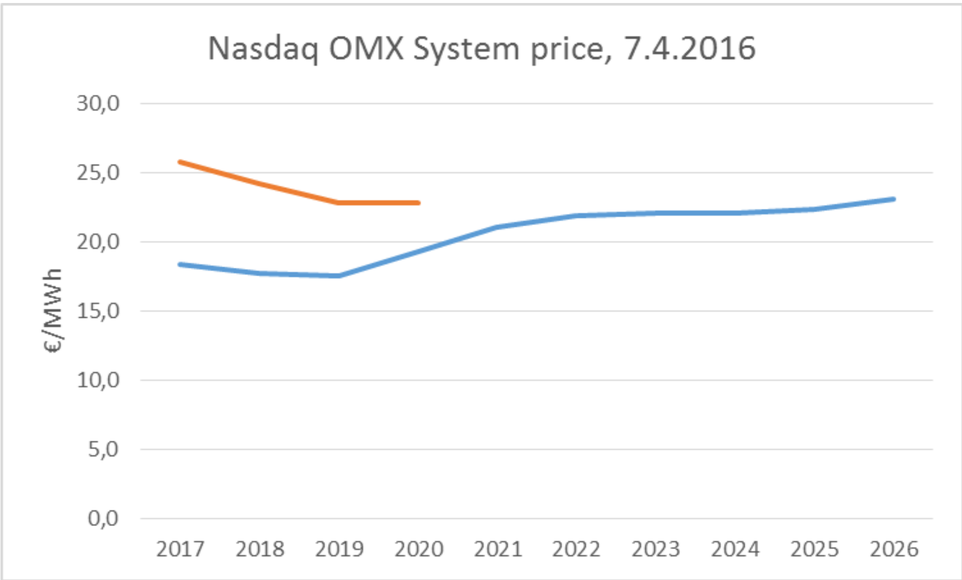

Figure 20. Nasdaq OMX Nordic system price evolution for the next 10 years. Finnish area price in orange, for the next 4 years. (Nasdaq OMX 2016.)

From Figure 20, one can see that the Finnish price is somewhat higher than the overall Nordic system price. This is largely due to the amount of imported power needed and bottlenecks in the Nordic transmission system. However, as new nuclear capacity comes into operation, the price gap reduces and the Finnish price will follow the system price more closely. This would mean that if current market conditions persist, the slow growth scenario would be the most accurate description of price evolution. Price spikes will most likely still occur due to cold peak demand periods. The market retains some degree of volatility as unexpected fuel price changes may occur as they have in the past, although updated energy and climate strategies will see efforts made to control the demand and the price of fossil fuels.

Market price historical development and expectations largely affect investments into generation capacity. Renewable investments are being made profitable through subsidies, however their share is not expected to significantly impact capacity during peak demand hours. Total wind capacity is expected to rise to around 3200 MW, of which about 6 % would be available during peak demand (Pöyry, 32). Annual production would reach the strategic goal of 9 TWh. Hydropower capacity stays largely as it is. The remaining condensing plants are expected to be closed if the market trend continues, as their variable production costs rise higher than the price of electricity. In addition, the profitability of combined heat and power (CHP) plants is threatened, and some of them might be replaced with heat-only plants. Plants that require modernization or other investments will be the first ones to go. Nuclear capacity evolves as expected by current new construction projects and decommissioning plans, with Olkiluoto unit 3 adding 1600 MW in 2018-19, Hanhikivi unit 1 adding 1200 MW in 2025, and Loviisa units 1 and 2 being decommissioned in 2027 and 2030 respectively, removing a total of 992 MW. The base case evolution of capacity shares and peak demand is presented in Figure 21. (Ibid, 17-26.)

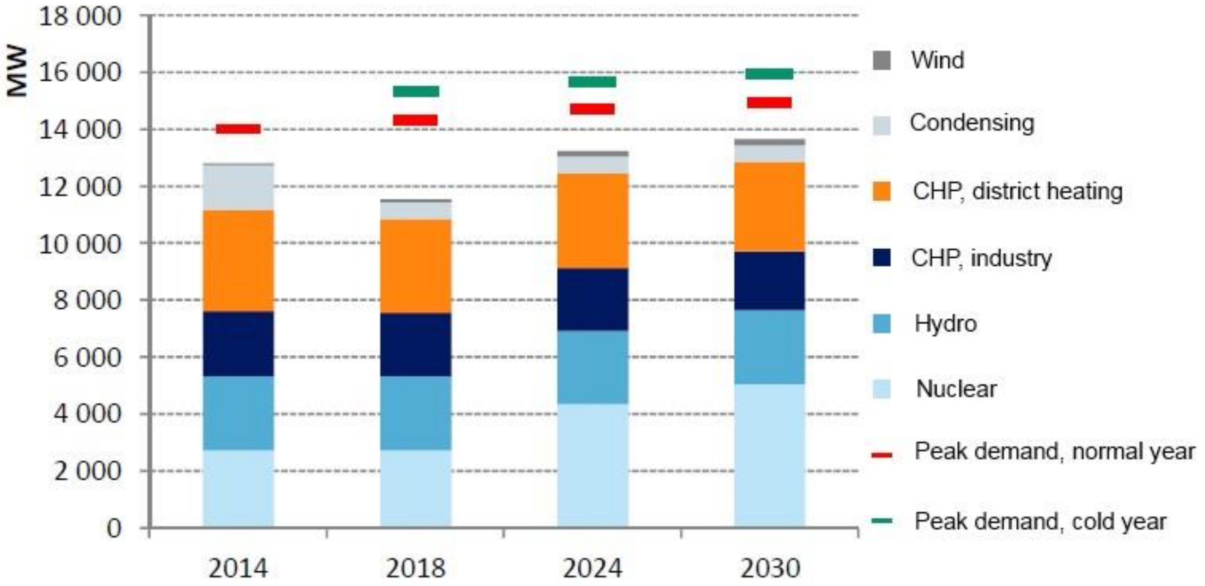

Figure 21. Evolution of peak demand and generation capacity shares up to 2030. Cold year indicates extreme conditions occurring once every 10 years. Base case. (Pöyry, 26.)

If the market trend continues as prophesized, it would appear that nuclear power remains marginally profitable during the 2020's, with increased profitability from 2030 and onward. With current variable production costs of 15-20 €/MWh, nuclear power plants retain a low profit margin from the early to mid-2020's (Vakkilainen et al. 2012, 11). With this in mind, the first life time extension period to 2038 will initially not be very profitable for Olkiluoto units 1 and 2. However, should the market prices evolve steadily along the lines of the slow growth scenario, later life time extension beyond the initial period may become viable.

7.3.2 Load Following Potential

Some European countries are discussing or have already established a capacity market, whereas Finland and the other Nordic countries still rely on an energy-only model. If a capacity market would be established, this would probably increase nuclear utilities' income, as nuclear power plants are able to provide firm capacity. This would be useful mainly during the summer months, when demand is low and renewable production is abundant. Oversupply and low demand lead to lower spot market prices. When market price falls below the production costs of nuclear power, power output could be reduced, thus reducing total production costs, but also generating income from the capacity that is now held in reserve. (Pöyry, 9.)

This kind of load following operation of nuclear power plants has been successfully implemented in France, where nuclear power contributes up to 75 % of the national energy production. Nuclear power plants have to deliver frequency regulation and adjust to low demand during night and weekends. Lately, as renewable capacity has increased, nuclear has also had to adjust to times of high solar or wind generation. (Persson et al. 2012, 2.)

The load following capability depends on the reactor's capability to deal with xenon. Xenon is a decay product of iodine – a direct fission product – and is a strong neutron absorber. During power operation, xenon reaches an equilibrium concentration, where as much xenon is produced from iodine as it is removed by absorbing neutrons and through radioactive decay. Alterations to the power level influences xenon concentrations. Reduced power means less absorptions and thus increased xenon concentration, which in turn further decreases reactivity and power. Load following operation requires the power level to be reduced significantly at times, meaning that the inevitable buildup of xenon concentration needs to be taken into account. This is done by using methods that increase reactivity in comparison to the decreased reactivity caused by xenon. PWRs can accomplish this by altering their primary circuit boron concentration. Boron is a dissolved neutron absorber used for reactor control in PWRs. Boron cannot be used in BWRs however, due to boiling taking place within the reactor. Instead, BWRs can influence the amount of boiling through altering the flow of the primary coolant. Boiling creates voids of steam in the water. Steam voids reduce the neutron moderation efficiency of the coolant, leading to decreased reactivity. Power reduction can be initiated by a reduction in coolant flow rate, with a later increase due to xenon buildup. As xenon levels stabilize, flow rate can be decreased again. An example of the effect of coolant flow rate on thermal power in a BWR is presented in Figure 22. (Ibid. 11-14.)

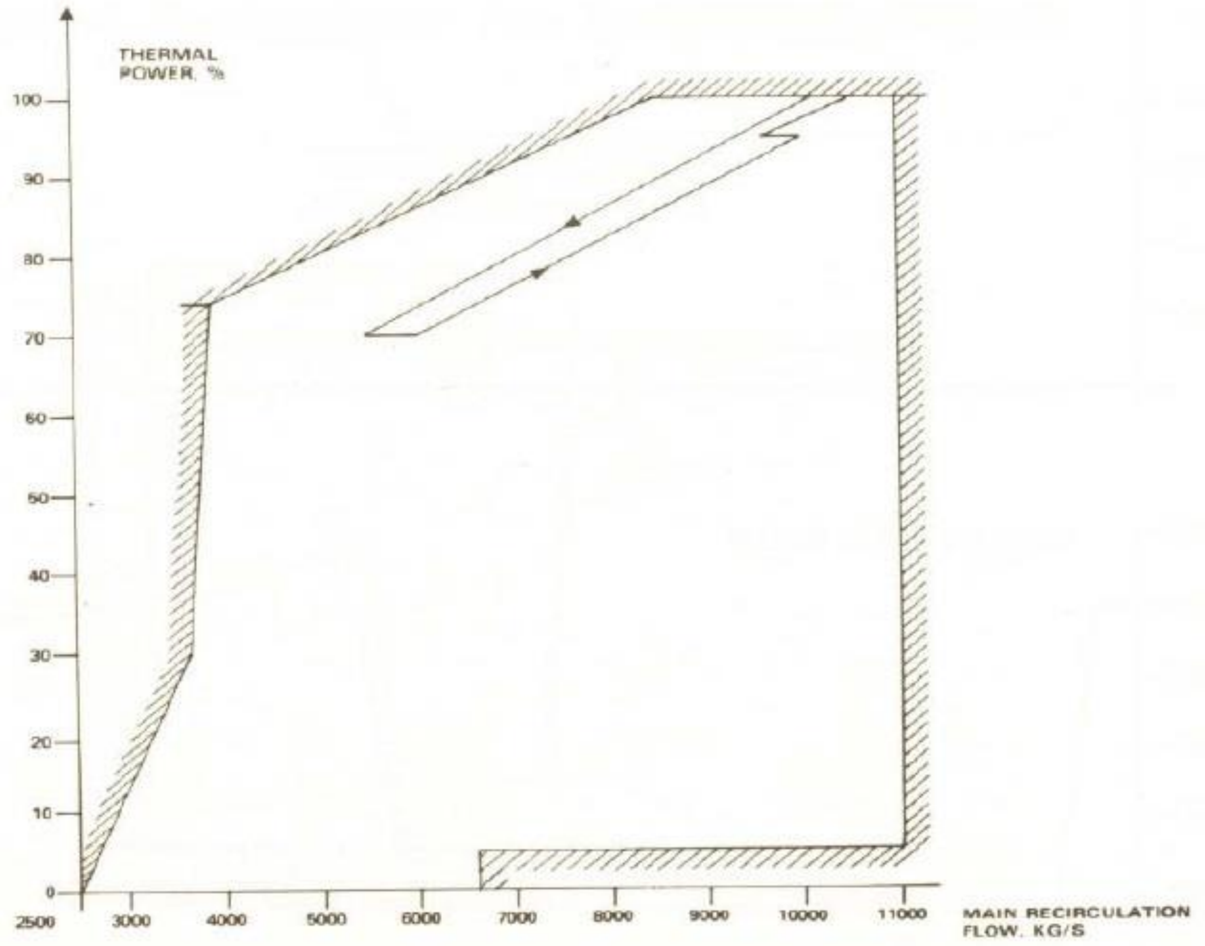

Figure 22. Power level reduction by reducing main coolant flow rate in a BWR, as indicated by the arrows (Persson et al. 25).

It is to be noted that load following operation of a nuclear power plant increases the amount of transients inflicted upon the reactor and related systems, resulting in increased ageing. Plants not designed for load following operation also experience increased wear on systems and equipment when operating at low power levels (below 60 %), as they are designed to operate at full power. Power levels above 60 % are less problematic. In conclusion, load following can be implemented to some degree, but design limitations and increased ageing effects have to be taken into account. (Ibid. 20-21.)

8 COMPARISON OF THE MODELS

Certain parts of the TVO process can be compared to the other processes explored in earlier chapters. Most common ground can be found with the Fortum process. The processes detailed in chapter 4.5 are focused mostly on economic evaluation and optimization. The UPM paper mill process has the least common ground, but some points can be considered. The comparison is done by looking at the different parts of the LCM process, mainly the information gathering, categorization, maintenance and modification planning, and optimization parts. The different tools and practices used by each model is presented in Table 4. In addition to the processes described in this thesis, two examples of Swedish nuclear utilities' LCM models are also included in the table. These models are only briefly described as part of the comparison, not in separate chapters.

Information gathering is not described in detail in the HydroAMP process. One can assume that generic condition monitoring procedures take place. The Durability method includes information gathering as a crucial part of the preparatory work before scenario comparison. The Westinghouse PAM method only specifies what kind of inputs are required for each strategy, but not the methods by which the information is to be gathered. One may assume that generic nuclear power information gathering takes place, including nuclear safety standard compliance and enhanced condition monitoring. The UPM paper mill process takes the next step from generic condition monitoring by using combined O&M personnel, thus allowing a cheap on-line condition monitoring system with personnel making observations of the equipment they are operating. The Fortum process uses much of the same information sources and gathering methods as TVO.

The HydroAMP, Durability and UPM processes all focus solely on production-related SSCs. Fortum uses Ageing Class and Maintenance Criticality Class as the main categories, while TVO's categorization is quite similar, without a separate Ageing Class. The PAM method is focused more on the economic evaluation part of the LCM process, so it does not as such include an SSC categorization phase.

All processes described in chapter 4.5 are focused on the optimal planning of maintenance and modifications. Fortum's maintenance strategies are quite similar to TVO's, with the exception of RCM evaluations conducted for certain systems. Modifications are planned according to differing needs. Optimization is conducted with a variety of tools ranging from HydroAMP's direct scoring system to the NPV change focused analyses of the Durability and PAM methods. The UPM paper mill process focuses on economical justifications for maintenance and modifications.

The Swedish models, from Ringhals NPP and Forsmark NPP, both utilize System Health Analyses. The input to these analyses comes from device and system experts and is compiled by specialized teams with a wide range of expertise. The result is a report for each system that details its condition and ageing prognosis for several years ahead. If indications for failure or otherwise unsatisfactory condition are detected or are to be expected in the future, analysts also include a list of suggested mitigating actions. Projects are prioritized using a special PRIMAL-model which determines the impact of the project on different categories, such as safety, production, environment, and costs. More recently, the utilities have begun moving toward a more risk-based prioritization system based on the ISO-55000/PAS-55 standards. (Lundqvist et al. 2016; Hägglund 2016.)

Table 4. Model specific tools and practices for each studied part of the LCM process.

Model	Information Gathering	Categorization	Planning	Priorization tools
TVO	System, device, unit function experts	Safety Class Maintenance Class	Ageing and Life Cycle Spread-sheets, LTP	Under Development
Fortum	O&M personnel, system experts	Ageing Class Maintenance Criticality Class	Ten Year Plan	Investment points RCM
UPM	O&M personnel	Production critical	Outage cycles	None
AMP	Maintenance personnel	Production critical	Annual maint. budget	Priority Rank
Dura-bility	Technical data, experts	Production critical	Scenario Comparison	NPV change, scenario timing
PAM	-	-	Scenario Comparison	NPV change, optimal scenario
Ringhals	System Health Analysts, O&M Personnel	Safety Class Quality & Function Class	7-year Plan, Long Term Plan, Life Cycle Thinking	PRIMAL, ISO-55000/PAS-55
Forsmark	Unit and system experts	Inspection Class	7-year Plan, Corporate Project Model	PRIMAL and PAS-55 combined

8.1 Strengths and Weaknesses

The HydroAMP model's strengths lie in the straightforward, systematic process and extensive priority criteria. The condition index and risk map score are direct methods for SSC comparison that can quite easily be determined for each studied SSC. There is also the potential for expansion, adding more criteria for comparison such as compliance with regulations. On the other hand, the model is somewhat lacking in accuracy due to its deterministic approach to risk. As it is used for hydropower analysis, the amount of regulation is also lighter than for nuclear power, so direct application to nuclear analysis would not be possible. Also, the method only assesses major power train components without further SSC categorization. Additionally, the investment prioritization only focuses on annual maintenance budgets, so there is no long term planning. However, lessons can be learned from the priority ranking system and similar, adapted methods can be applied to nuclear power analyses, especially when considering investment budgets.

The EDF Durability method has a clearly defined, step-by-step process that includes information gathering and SSC screening. It can thus be used to identify improvement needs and compare improvement alternatives to a base case. By looking at mean NPV value changes over time, the method is excellent for optimal timing of improvements. However, the method uses point estimate values and thus the outputs have some uncertainty to them. Additionally, this method is also used for major power train components, so analysis of safety-related SSCs would require modification to include more extensive risk assessment and information on regulations.

The Westinghouse PAM model is excellent for scenario comparison, as it presents data as probability distributions, allowing for uncertainty analysis and risk-informed decision making. There are also several different strategies than can be selected as alternative scenarios. The PAM model is more suited for nuclear power applications, as can be seen from the example in Appendix IV, where it is used to solve a standard LCM problem. However, the PAM model is more of a tool than a complete process, so it lacks any specific system for information gathering and SSC categorization. Instead, it falls to the user to gather and provide the necessary information for the tool to make its calculations. The user must also define its own SSC categories. In other words, PAM is more of a tool to be used as a part of the LCM process, mainly for optimal maintenance or modification scenario selection.

The Fortum Process has a strong information gathering and SSC categorization system in place. The implementation of an Ageing Class to be used specifically for selection of SSCs important to plant life makes for more accurate targeting of ageing mitigation measures. In other words, focusing more on the plant life critical SSCs and less on ones that have lesser impact leads to increase in plant availability with a smaller overall LCM cost. Modification investment prioritization is still somewhat lacking, although improvements are on the way. Especially the score system for investments, with different areas and success probabilities, might see more efficient investment prioritization in the future. The Fortum process also lacks plant-wide overview and analysis that would extend further than the current, system-wide basis.

The UPM paper mill process approaches LCM from a more industrial view, with the main goal being production availability and quality. A solid flow of information is in place from condition monitoring to investments. This is strengthened by the use of operative maintenance knowledge. Operators with a maintenance background, or maintenance personnel retrained as operators are effective at identifying failure indicators as they can make observations during their normal operative duties. They are also quite familiar with the machines they operate, so any anomalies are quickly noticed. SSC categorization is problematic at the moment, as it has been done haphazardly and without proper background information, thus leading to an abundance of “critical” SSCs with inflated importance when related to the production process. A re-categorization is underway, however. Due to oversupply of the paper market, modification investments are scarce and often done only by necessity, i.e. when production will cease without a replacement or refurbishment. Therefore, no investment prioritization structure is in place. (Pasanen.)

Ringhals and Forsmark has quite similar models and practices regarding LCM. Information gathering is somewhat different, Forsmark utilizes system experts while Ringhals focuses on device experts. The problem with focusing solely on device experts is that system information must then be extracted from several device reports during the System Health Analysis, when no direct system knowledge is available. Otherwise, the analyses work in the same manner. The analyses have excellent details on both current and predicted future condition, as well as proposed mitigation actions for any perceived ageing effects. Ringhals has also conducted an extensive RCM project, upon which it bases its maintenance strategies. Obsolescence issues are being tackled at Ringhals through joining the Rolls Royce POMS-program, and at Forsmark through streamlining the spare part acquisition and shelf life replacement process. Prioritization has also been conducted for some time, with the older PRIMAL-model being partly replaced with new, risk-matrix-based models formed from the ISO-55000/PAS-55 standards. Ringhals encountered some problems with the PRIMAL-model due to being in a phase where several modernizations were required to continue operation, thus leading to an abundance of top priority projects. Forsmark reports a more even spread of priorities with the PRIMAL-model. (Lundqvist et al.; Hägglund.)

The TVO process has an excellent information gathering structure, with the allocated device, technical and system experts. The unit function analysis has not been operating as planned, so wider, system-spanning assessment is lacking. Categorization is also well organized, although lacking a specific, LCM focused class such as Fortum's Ageing Class. There is a good system for long-term planning that allows even more distant upcoming SSC issues to be addressed and prepared well ahead of time. Maintenance is conducted more evenly than in Fortum's process, as reliability centered maintenance is not used. Thus, even SSCs less critical to plant life are maintained in good condition. This can be both a strength and a weakness, depending on perspective. On one hand, this leads to a higher overall availability of plant systems, while on the other hand maintenance costs are somewhat higher for less important SSCs. Prioritization of modification investments is still lacking, however some improvements are already under way.

8.2 Improvement Options for TVO LCM

Observations made of the TVO process, as well as the comparisons made in the previous chapter, have led to the discovery of certain improvement options for TVO's LCM process. The improvement options are partitioned into the three main parts of the process, information gathering, project and maintenance planning, and investment planning.

8.2.1 Information Gathering

TVO has proposed one solution for the problems described in chapter 7.1.5. The information flow from source data to investment decisions is to be changed in such a way that investment proposals get delivered in time and that sufficient expertise is available to consider and prioritize the investment proposals before they are submitted for budget approval. The new information flow chart is illustrated in Figure 23. (Vaaheranta.)

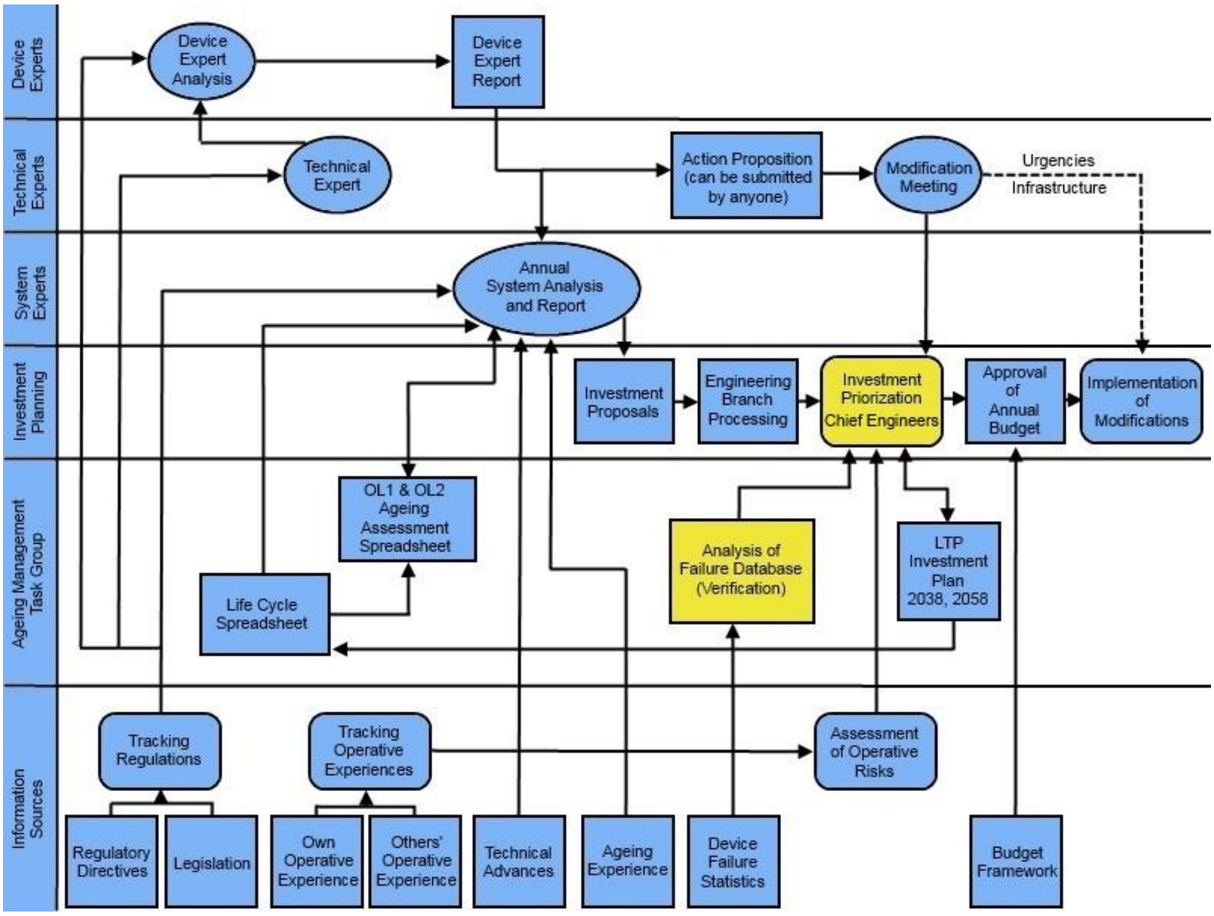

Figure 23. Improved information flow chart for investment planning (based on Vaaheranta).

The need for system-spanning expertise is apparent. TVO is currently working on introducing a group of chief engineers from each engineering field that convene bi-monthly and review the condition of each system in order to identify upcoming projects. The chief engineers can then well in advance notify the system experts on cases which will need investment proposals in the coming year. This results in better prioritization of investments, so that the correct investments can be made at the correct date. (Ibid.)

As the information flow from data sources to investment propositions is relatively slow, a verifying analysis linked directly to the chief engineer group could be useful. The analysis could be based on device failure statistics, from which up-to-date information can be collected on which devices are failing often and which are not. Comparing the failure statistics to the incoming investment proposals, the chief engineers can then verify which investment proposals are indeed viable and whether there are discrepancies that require further investigation or justification. (Ibid.)

The Action Proposition system is revised in such a way, that the chief engineers handle also review the propositions during their monthly meetings. Only urgent modifications and infrastructure improvements (which do not tax the same resource pool) are directed straight to implementation. This way, resource allocation can be optimized and focused onto the important projects. (Ibid.)

The life cycle and ageing spreadsheets should be linked together. Adding preliminary information on project costs and resource needs would add significant value to the life cycle spreadsheet, as then it can be used for more accurate project timing without overcrowding outages. Linking to the ageing spreadsheet, notifications on projects progressing for systems in poor condition allow for better transparency so that system experts are aware if and when something is being done. The current risk assessment of the ageing spreadsheet should be linked to the Risk Assessment department's system, so that both use the same scale. A simple representation of the linking of spreadsheets is illustrated in Figure 24. (Ibid.)

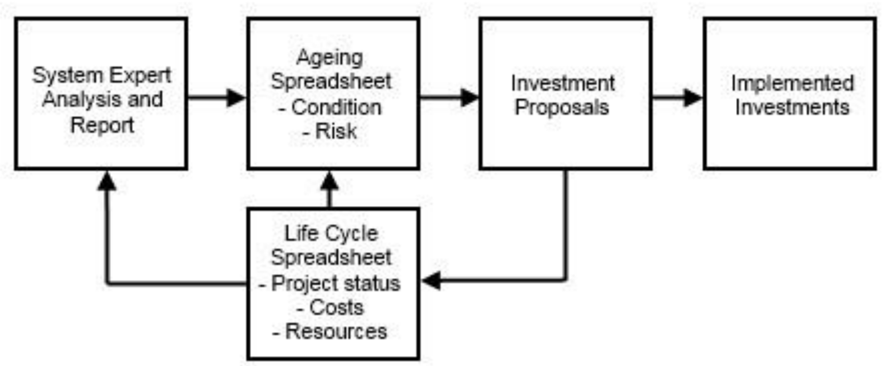

Figure 24. Linking of Ageing and Life Cycle Spreadsheets to the investment process.

By keeping an updated database on system condition and risk levels, as well as project status, costs and resources, it is possible to better prioritize investments according to urgency. Timing of investments can also be optimized once rough numbers of project costs and resource needs are listed. This way, overburdening outages is also avoided. System experts can check the status of their suggested project investments from the life cycle spreadsheet, and know how long they may have to wait for improvements. (Ibid.)

In addition, a proactive approach to obsolescence management would be necessary, especially due to the long licensing procedures of safety-related SSCs, which can take up to three years (Hassinen 2016). SSCs where both physical and technological ageing are observed should be prioritized in this matter, especially if licensing is required. Spare parts are normally managed by the maintenance department. However, if spare part obsolescence is discovered, the selection and licensing of a replacement part is conducted as a modification project by the technical services department. Moving the spare part replacement duties to the organization which normally deals with spare parts could be beneficial. This would also free up resources from the technical services department to take part in other modification projects. Incorporating an external obsolescence database service, such as the POMS database used by Loviisa and Ringhals, could also be useful for keeping track of obsolete equipment and possible new vendors. Continued co-operation and information sharing with Swedish utilities is also of importance to keep up to date on operative experience from the similar plants operating in Sweden. (Vaaheranta.)

8.2.2 Project and Maintenance Planning

As Action Propositions and System Experts initiate modification projects, there should be some kind of documentation available on each project as early in the process as possible that provides some background information. For example, the following information could be included in the document:

- Background and objective.
- Scope.
- Current situation.
- Problems and directives.
- Risks.
- Cost assessment.
- Impact on outages.
- Accessory material.
- Proposed plan of action.

- Time table, resource allocation, responsibilities. (Palomäki, 6.)

With this information available in an early phase, it can be used as a part of the approval process. If a project is approved, an alternate scenario is chosen, or the project is discarded, the information will then be updated to the document together with reasons why the particular choice was made. Information may be omitted, but in that case justifications why information is missing must be included. An example of this would be that a project does not impact outages because it can be executed during normal operation.

Fortum's and the Swedish utilities' RCM approach has shown the potential benefit of increased reliability for certain systems. However, RCM analysis is resource-intensive, and should not be undertaken unless reliability increases provide significant benefit, for example for systems that deal directly with production or critical safety measures. An RCM approach would also decrease the amount and thus cost of maintenance for less important SSCs.

8.2.3 **Investment Planning**

The chief engineer group plays an important role in the investment planning process. A system for priority ranking projects has already been researched and implemented in a priority spreadsheet system, with several columns with different criteria for priority consideration. Importance to company strategy, short and long term costs and effects, as well as project risks all add up to the priority ranking. Implementation of this sort of ranking system could prove beneficial and provide a tool for the chief engineers to compare the impact of different projects. Certain criteria should be given increased importance, however. Especially if a project is critical according to regulations, it should immediately be given a top position on the ranking list, as such a project is basically a forced investment.

The priority spreadsheet is quite heavy, so ranking projects can be quite bothersome. The criteria are also somewhat unbalanced, as the regulatory compliance is only one criteria among others, without an especially high weight as it should have. A combination of the spreadsheet and a scoring system similar to Fortum's lighter model or the Swedish PRIMAL-model could be useful. Compliance with company strategy should still be assessed, but the other criteria could be somewhat simplified into safety, ageing, production, environment and other benefits such as short payback time and reduced O&M costs. The main purpose of such a ranking system would be to only serve as a tool to help the chief engineers organize and prioritize project investments. It should by no means be an absolute measure of importance, but a rough estimate, a supplement to the expertise of the group. If further comparison between alternate scenarios is desirable, using tools such as the Westinghouse Proactive Asset Management can be considered.

8.3 Economic Benefit Potential

The cost sources of a project can be divided into preliminary work, such as plans and studies, and executive work, such as manufacturing, installation and commissioning. For components that need a nuclear safety validation in order to be used as a part of a nuclear facility, there are additional costs due to the extra validation work. The validation process is also linear and takes a significant amount of time to complete. (Hassinen.)

The scope and complexity of the safety validation depends a lot on the technology and Safety Class of components involved. The most expensive components can be up to 10 times more expensive than a similar, non-validated component. On average, a safety validated component can be assumed to be 5-6 times more expensive than a non-validated one. The major factors contributing to the cost of a non-validated component can be seen in Figure 25. (Ibid.)

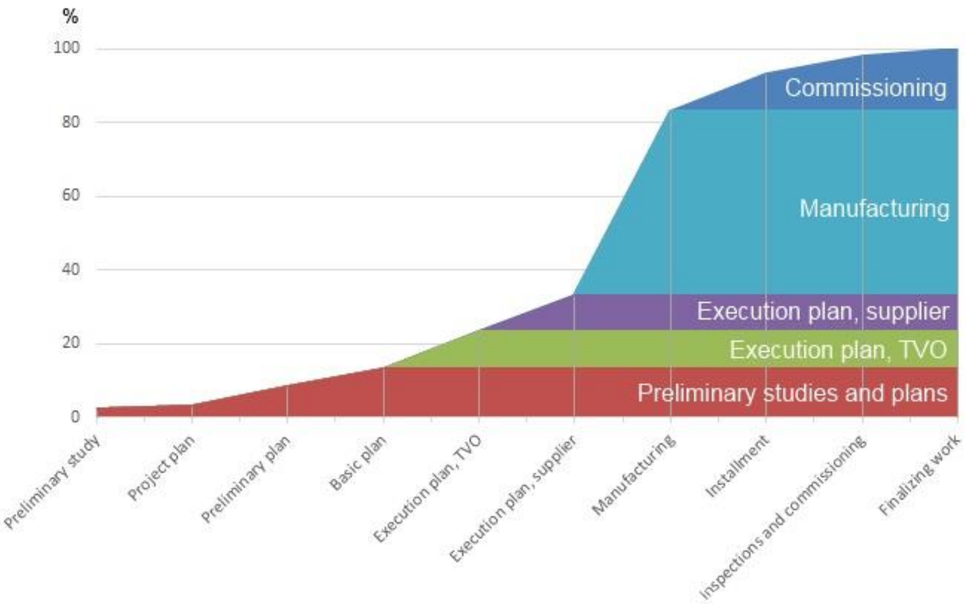

Figure 25. Cost accumulation over the project lifetime of a component that does not require nuclear safety validation (Palomäki 2016).

For a component that does not require nuclear safety validation, the largest cost share is by far that of the manufacturing phase, which is around 50 %. Project planning costs are only around 35 %, while installation, commissioning and other finalizing work account for the final 15 %. By comparison, the major cost factors of a component with nuclear safety validation is presented in Figure 26. (Hassinen.)

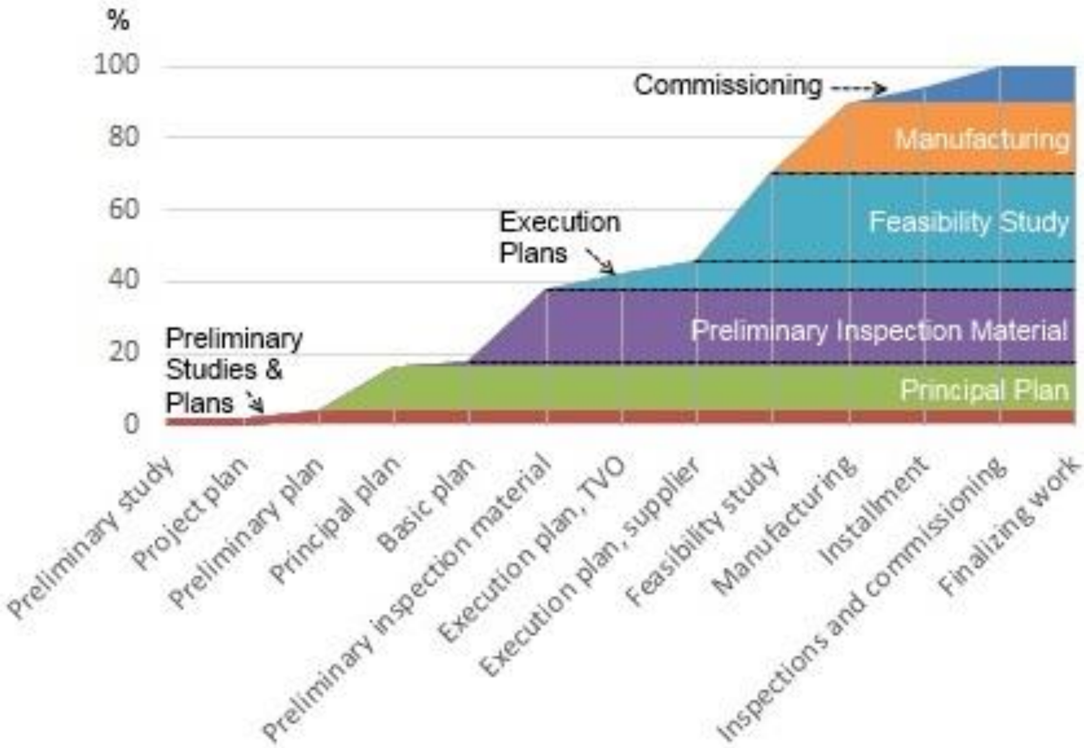

Figure 26. Cost accumulation over the project lifetime of a component that requires nuclear safety validation (Palomäki 2016).

For a nuclear safety validated component, the pre-manufacturing phase of the project accounts for the lion's share of the costs, up to around 70 %. This phase now includes all validation work required to ensure the component is suitable for a nuclear safety environment. When comparing component prices, this is the part that causes the huge difference in price for "normal" components and ones sold to nuclear facilities. (Hassinen.)

The validation process typically has three phases, where the impact of a modification project upon the plant, its systems, and devices is studied, depending on the scope of the project. The validation process requirements are described in the YVL-Guides. For example, if a new device is acquired, the process progresses as follows:

1. Principal plan (plant phase): Will there be changes to plant design basis? Which organizations will be involved in the project? What are the changes to plant documentation? What safety validation documents will be submitted during the project? The principal plan is submitted to STUK for approval, this process usually takes about one year. For bigger projects, this phase must be completed before investment approval can be granted.
2. Basic plan (system phase): How does the project impact system functions? This phase includes producing all preliminary inspection material which is sent to STUK for approval, which takes another six months.
3. Execution plan (device phase): In this phase, the device manufacturers can be vetted and audited. Feasibility studies, as well as plans for design, construction, validation, testing and execution are made. Again, the plan is sent to STUK for approval. This phase takes about two years to complete, after which actual manufacturing and commissioning can take place. (Ibid.)

The three phases take a total of three and a half years to complete. This can be significantly longer if documentation is not approved by STUK but sent back for correction. Incomplete documentation can significantly lengthen the period of safety validation. There is also a lot of paperwork involved, depending on the scope of the project. For a large project, the principal plan can be one document, the preliminary inspection material 25 documents, and the execution plan closer to 100 documents. This amount of paperwork and the long time it takes to process them can be daunting for many manufacturers, which is one reason why prices are set so high for nuclear safety validated components. (Ibid.)

As the utility is more used to interact with the regulatory authority and has more insight into the use of the YVL-Guides than most manufacturers, it would be preferable that the utility takes onto itself most of the validation work. This way, documentation will be more easily approved, as they are less likely to lack critical information. Expertise in using the YVL-Guides should be cultivated, and dialogue with the regulator encouraged in uncertain cases. The manufacturer is only required to provide the necessary data on their product. This way, the validation process can be sped up, and the price tag on the manufacturer’s product becomes lower. Of course, this requires committing utility resources to the task. It is still better to have a dedicated team of experts within the company doing validation work which is regularly required in the nuclear industry, than externalizing it to manufacturers that very rarely produce nuclear safety validated components. Also, once a manufacturer has learned the validation process, it can significantly raise the price of its product, as it can conduct the validation faster and more smoothly than its competitors. Internalizing the validation work has the potential for cost savings of millions. On the other hand, unnecessary validation work should be avoided. A project that does not involve components that need nuclear safety validation should not need to engage in unnecessary bureaucratic measures but instead be implemented with only the required levels of planning. Making sure that unnecessary paperwork is reduced also impacts the cost and time table of projects. (Ibid.)

9 CONCLUSIONS

Life cycle management can be seen as the main process that counteracts plant ageing and upholds SSC availability in an economic manner. It often involves several organizations and fields of expertise. It relies heavily on the amount and quality of information available regarding SSC ageing and condition, as well as efficient information transfer within the process. In nuclear power, it would seem that optimization of LCM procedures has not been a priority earlier, when electricity prices were high and return on investment assured. As electricity prices are falling closer to the cost of production, even nuclear power utilities have begun to see the need for economic optimization, the optimal timing and prioritization of LCM investments.

The life cycle management process at TVO has several strong points, but there is still room for improvement. Information gathering coverage is extensive, with experts dedicated to monitoring the status of devices and systems. Technical experts further assist the device and system experts by providing information on specific fields of technology. A larger, system-spanning overview is missing, however. This is necessary in order to identify issues that affect several systems, related modification needs and common cause failure modes. Obsolescence management is also still reactive and needs to be addressed.

The process of SSC categorization is clear and efficient. The classes are selected through asking the proper questions and are used to select optimal maintenance strategies. Modification optimization is still somewhat lacking, as there is currently no system for timing and prioritizing investments. A group of chief engineers, who will also provide system-spanning expertise, are to be the main organ that sorts and initially prioritizes investment proposals. By convening on a bi-monthly basis, the group will stay up to date on plant condition and also be able to assess action propositions that are submitted in a steady stream throughout the year. Additional assets that the chief engineer group could use as assistance in sorting and prioritizing investments include a scoring system, PRA with economic criteria, and scenario comparing tools such as the EDF Durability method or the Westinghouse Proactive Asset Management method. The prioritization models used and investigated by the Swedish utilities could also be adopted to assist in prioritization of TVO’s projects.

As for the long term planning, there are decent targets set according to the projected plant life times, which include all major modifications required to maintain safe and productive plant operability until those target years. However, for the more distant projects there is little documentation or background information on the reasoning behind the projects, why they are necessary, and whether their time tables are flexible or not. A basic documentation or background data sheet of each project could provide increased transparency and be used as reference when beginning project preparations. This basic information document usage could be extended to other, smaller projects as well as action propositions.

The System Health approach used by the Swedish utilities also deserves some consideration. With a long-term ageing prediction included in the condition analysis, it is possible to better assess when at the latest actions need to be taken to mitigate ageing effects. A more comprehensive life cycle study could also be useful, where systems or technical areas (electrical, I&C, etc.) assess what large measures need to be taken in the future to ensure safe operability. When needs arise, this larger plan of action can be consulted to check if said needs are going to be satisfied with some of the upcoming larger measures. A database tool of a similar approach is already under development.

These changes could help TVO to increase information flow effectiveness, make sure the correct investment proposals are submitted on time, and ensure that the correct plan of action is chosen when comparing different scenarios. Increased transparency of the long term plans means that shareholders can rest assured that the correct projects are being undertaken with some background knowledge into why each project is necessary.

10 SUMMARY

Life cycle management is a process that aims to counteract plant ageing. It consists of a technical analysis phase and an economic optimization phase. The technical analysis includes gathering information on ageing mechanics, ageing effects and equipment reliability, as well as categorization of plant systems, structures and components according to their susceptibility to ageing and the significance of their failure. The technical analysis also produces different strategies to counteract the ageing effects or to enhance equipment reliability. The economic optimization phase compares different strategies and attempts to find the optimal strategy to be implemented at the optimal time. A process which only focuses on counteracting ageing effects of SSCs related to nuclear safety functions is known as ageing management.

The technical analysis of the LCM process includes gathering information on SSC ageing and failure rates. Ageing is defined as physical degradation or technological obsolescence. Physical degradation is mainly caused by operating conditions and environment, as well as the different stress, strain and wear caused by operation. Technological obsolescence is somewhat different for systems than for structures and components. System obsolescence occurs when, for example, regulations are updated in such a way that a safety system no longer fulfils the requirements. Structure and component obsolescence occurs when original manufacturers go out of business, new products replace the old ones or tech support is no longer available. Obsolescence also occurs if new technologies that materially improve safety, reliability or performance become available. Any time when new components are considered, it is important to identify whether they introduce new failure modes to the system.

Risk assessment is used to compile data on SSC ageing and condition to produce failure probabilities and consequence probabilities for each SSC. These can be used when categorizing SSCs according to their importance to safety and production, as well as identifying SSCs that either have a high risk contribution, a high failure probability, or both and thus need mitigating actions. Risk assessment can also be used as a tool when comparing and optimizing LCM investments. Maintenance strategies are selected according to SSC categorization, focusing more intensive maintenance and condition monitoring measures on SSCs that have higher impact on safety or production, or whenever maintenance is economically justified. When significant degradation or failure rates are observed despite maintenance actions, or if technological obsolescence occurs, plant modifications may be needed in order to correct the situation. Modifications are larger projects that replace old SSCs with new ones, or introduce completely new SSCs to complement the existing ones. The need for these projects are often identified long beforehand, so that they can be planned and timed accordingly.

Economic optimization means the selection of the correct maintenance strategy or modification solution for each situation. Correct SSC categorization makes the maintenance selection significantly easier. Modification optimization is more difficult. In order to optimize the modification project investments, one needs to know the economic impact of each alternative solution with enough accuracy that the alternatives can be compared. Also, finding the optimal time to implement each solution requires enough knowledge of the risk impact of delaying a project and how it affects failure probability.

There are some additional features of nuclear power that need to be taken into account when considering LCM. Nuclear power plants tend to have fairly long design life times, which means that during operation both technology and regulations are bound to change several times, leading to technological obsolescence issues. Keeping equipment in good condition and the plants operating safely and reliably also contribute to good public image. This is beneficial as public opposition of nuclear power can lead to political pressure and increased regulation or taxation. Major projects are also often related to license renewal. Operating licenses are renewed between certain intervals which depend on national legislation and regulation.

When approaching end of design life, nuclear power plants can be evaluated for life time extension if major plant SSCs are still in good condition. Most of the time, larger components such as steam generators may need extensive repairs or even replacements when faced with extended operation. Life time extension related projects are massive and can have dire consequences if not managed properly, or if their planning has been inadequate. One example of such a problematic project is the cracking of the containment concrete dome of Crystal River Unit 3 when an opening was made in preparation of steam generator replacement. Another example is the significant tube wear discovered in new steam generators after only one operating cycle at San Onofre Units 2 and 3. Both cases lead to premature plant decommissioning and significant losses for the utilities. When dealing with complex technology and large plant modifications, it is important to make sure that all options have been assessed and all failure modes researched.

In Finland, nuclear power regulation is provided by the Finnish Radiation and Nuclear Safety Authority. The regulator, STUK, derives its authority from the Nuclear Energy Act and several Government Decrees that provide the framework for safe nuclear power production. STUK publishes a series of guides that utilities use in their ageing management procedures. STUK also reviews all documents and applications provided by the utilities related to licensing and other nuclear safety related projects. For benchmarking purposes, the domestic LCM processes of Fortum Loviisa NPP and UPM Paper Mills are explored, as well as some literary sources from abroad. Other nuclear viewpoints are gained from the Swedish NPPs at Ringhals and Forsmark.

The TVO LCM process consists of information gathering, maintenance and modification projects. Information gathering is conducted by specific device, technical and system experts that each are responsible for their respective areas of expertise. The information is processed into reports that present the status of each device or system and identify improvement needs. From an LCM viewpoint, the most important SSC categories are Safety Class and Maintenance Class. Maintenance Class is used for maintenance strategy selection. Safety Class relates SSC importance to upholding nuclear safety, which is relevant as such new SSCs will need licensing. Larger modification projects are entered into a long term plan. Currently, there is no prioritization system or system-spanning expertise used in investment optimization but a solution is being implemented, in the form of a chief engineer group.

The chief engineers will convene on a bi-monthly basis to review the plant condition, identify possible improvement needs and sort through any action propositions made since the last meeting. The chief engineers will also be able to recognize which investment proposals should be coming in each spring and point these out to the relevant system experts. The chief engineers will work closely with the long term plan, as well as other tools used to identify modification needs.

In the past, nuclear utilities have had better return on investment due to higher electricity prices. As prices decline and come close to the current cost of operation, investments will need to be prioritized and some even delayed or discarded if enough justification for implementation cannot be found. The increase of Nordic renewable energy greatly lowers market prices during times of high wind or solar power, like in the summer. During winter, renewable production is low. This imbalance between seasons will see good prices during the winter but low prices during the summer. A transition toward more capacity driven markets may prove a solution for nuclear utilities in the future. Nuclear power plants have the capability to reduce their output during times of low demand and low electricity prices, yet still be able to ramp up their power fairly quickly when required to. However, load following operation also increases the amount of transients the plant is subjected to, thus accelerating plant ageing.

The TVO process fares well when benchmarked with the other studied processes. Its strengths lie in the extensive information gathering system and maintenance and project planning expertise. Its weakness lies in the lack of centralized system-spanning expertise and lack of optimization for modification investments. There is still room for improvement, and useful tools discovered from the other processes that could be utilized. One such improvement would be the implementation of investment optimization tools such as the ones used by EDF Durability Method, Westinghouse PAM, or used by the Swedish utilities.

In conclusion, it is important to have a well-functioning life cycle management process in order to safely, reliably and productively operate a nuclear facility until the end of (and beyond) its design life. TVO manages their ageing plant fairly well, but with the falling electricity prices an economic optimization of the process becomes necessary. Luckily, there are several optimization tools already available, from which lessons can be learned and implemented into the TVO process. Some of these changes are already underway, but there is still room for additional improvement. Implementing additional documentation for long term projects, as well as investment ranking tools for modification investments may assist in justifying and prioritizing larger investments in the future. Internalizing the licensing of nuclear safety components may also provide some quite significant cost savings.

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APPENDICES

Appendix I: Fault and Event Tree Examples

On the SSC level, a fault tree is a representation of SSC failure causes through Boolean algebra. It consists of a result event (SSC failure) at the top of the tree and all the identified factors that can contribute to failure as the branches. Failure rates of the root causes are known values or probability distributions. The root causes are connected to the top event through logical gates representing the conditions for SSC unavailability. An example fault tree is represented in Figure 27. (Vaurio 2012, 99.)

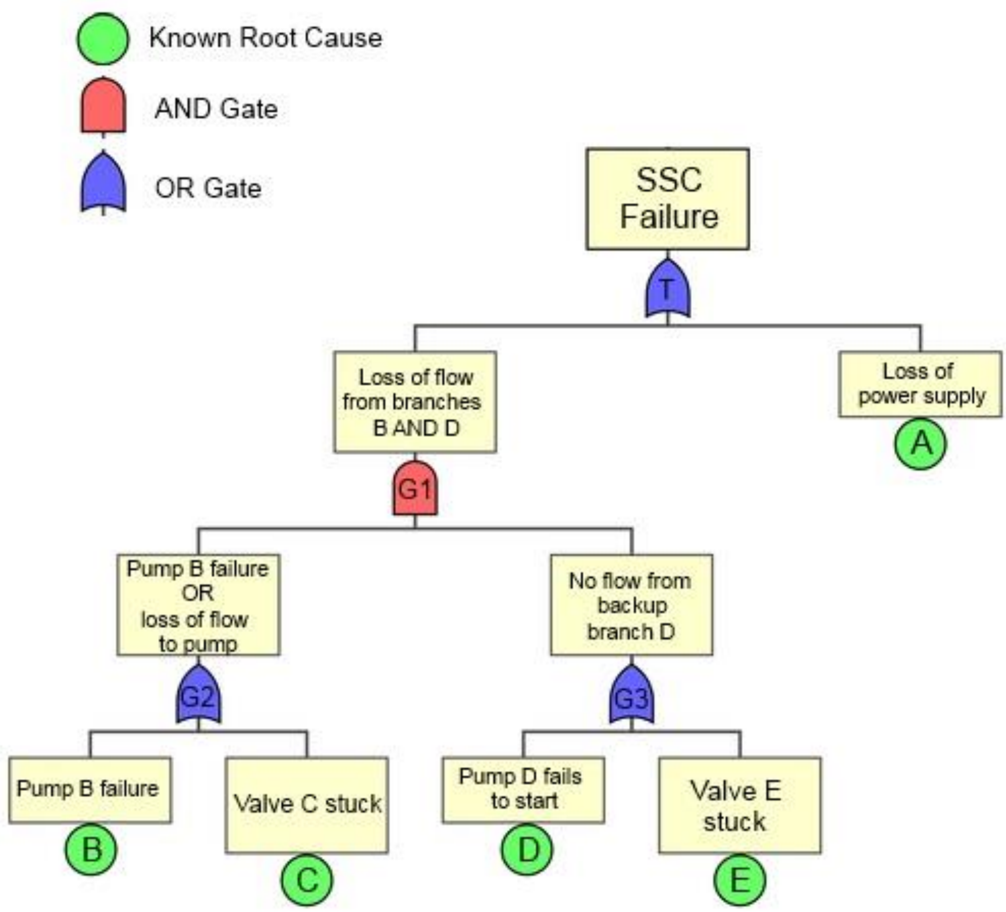

Figure 27. Example of a fault tree diagram. Identified root causes leading to SSC failure. (Long 2008.)

The fault tree in this example consists of all identified events leading to the failure of the SSC (top event T). In order to fail, the SSC must experience loss of power supply (event A), or loss of flow (gate G1). Flow normally comes from branch B (gate G2), but there is a backup branch D (gate G3) in case of branch B problems. Branch B flow loss occurs if pump B fails, or valve C is stuck (events B and C). Upon failure of branch B, backup flow is attempted by starting pump D (event D). If pump D fails to start, or if valve E is stuck (event E), the backup branch also fails to provide flow. So in case of both branches B and D failing, loss of flow is experienced and the SSC fails. Failure probabilities of the root causes are known, and through them the failure probability of the SSC can be calculated.

In order to assess the consequences of SSC failure, event trees can be constructed. The event tree consists of an initiating event, such as an accident or unexpected transient, and the event chain of mitigating the effects of that event. Safety systems or backups are integral to the mitigation process, so probabilities of their success and failure can be obtained from the fault tree. Finally, the consequence of each safety system succeeding or failing are listed. Event trees can also list possible economic loss for each branch, giving an estimate for the economic significance of each system. An example event tree is shown in Figure 28. (Vaurio, 116.)

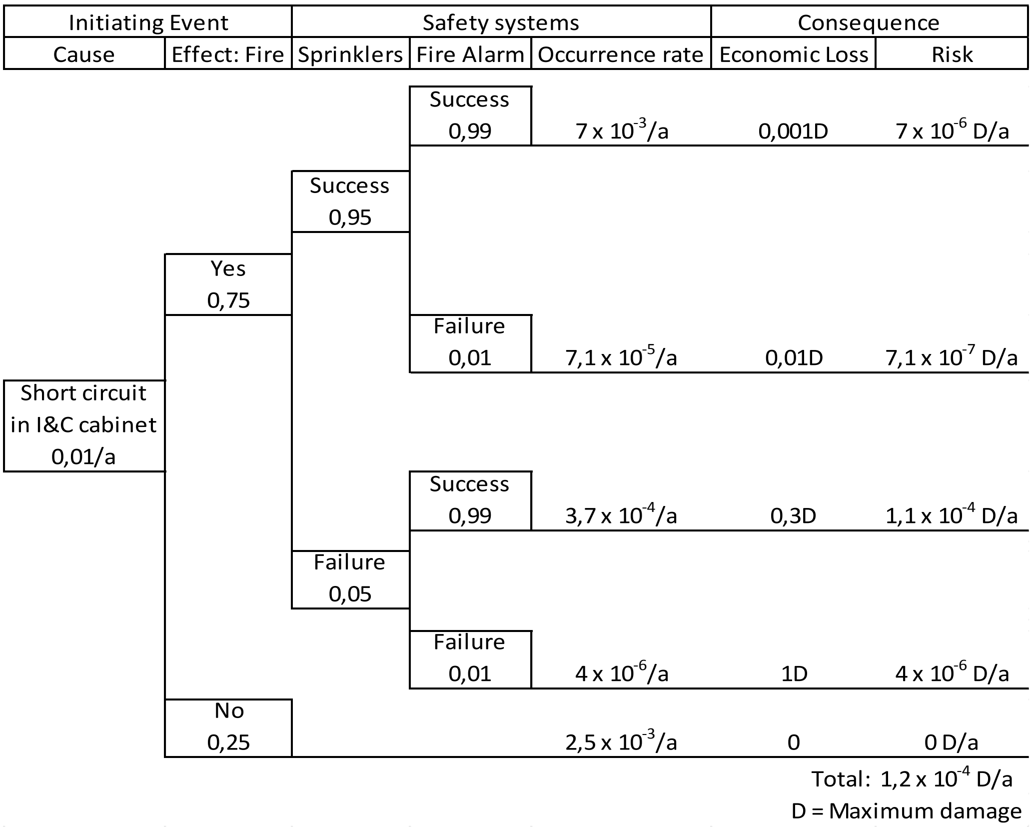

Figure 28. Event tree of a short circuit caused fire. D represents the maximum economic loss caused by fire damage. Final risk is represented as probability of damage per year. (Vaurio, 116.)

The example event tree in Figure 28 shows the probability of a short circuit in an I&C cabinet causing fire damage and thus economic loss. The frequency of a short circuit occurring is derived from experience. In this example case the frequency is 0,01 events per year, in other words once in 100 years. The probability of a fire starting from the short circuiting is 75 %. In case a fire does not start, the event is considered to be resolved without material damage. Safety systems present to mitigate fire damage are sprinklers and an automated fire alarm (which calls firefighting personnel). The failure probabilities of the safety systems are derived from their individual fault trees. The best case scenario in case of fire would be both sprinklers and alarm activating, minimizing the material damage to 0,1 % of the damage caused in the worst case scenario, where the fire rages on unchecked. Other possibilities include one of the safety systems failing but the other succeeding, where the failure of sprinklers is considered to lead to more damage as fire suppression is not begun until the firefighters arrive.

The occurrence frequency and damage potential of each scenario is multiplied to solve the risk factor of each scenario. The risk factor represents the probability of damage caused by each scenario per year. The total risk factor represents the probability of I&C short circuit fire damage per year.

Appendix II: HydroAMP Examples

Table 5. Condition indexing of a hydropower plant's power train components (Bachman et al. 9).

Evaluated Components	Unit 1	2	3	4	5	6	Component Weights
Generator	2,9	6,8	8,9	6,0	7,8	9,0	0,30
Transformer	5,0	6,0	2,3	7,3	5,4	4,0	0,25
Turbine	6,4	4,3	8,0	2,3	4,2	5,0	0,20
Governor	4,2	6,9	5,0	5,9	2,0	6,3	0,10
Exciter	8,4	2,9	6,0	6,7	7,0	3,5	0,10
Circuit Breaker	9,0	5,0	7,3	6,5	2,0	9,0	0,05
						Sum	1,00

The condition index in Table 5 ranges from 0-10. Poor condition lies in index range 0-3, fair condition in range 3-7 and good condition in range 7-10. In order to assess maintenance need, a condition threshold value has been set for condition index 3,0. Components in fair or good condition (index > 3) are assigned their corresponding component weight value, while components in poor condition (index < 3) are assigned the value 0. This gives a modified condition rating which can be used to indicate unit and station condition (index range 0-1). It is determined that if the unit index is below above 0,85 the unit is in good condition, while if the index is below or equal to 0,75 the unit is in poor condition and in need of maintenance. Modified condition ratings are shown in Table 6. (Bachman et al. 9-10.)

Table 6. Modified condition ratings when component condition threshold is set to 3 (poor) with unit index as a sum of component values. Station index is the average of all unit indexes. (Bachman et al. 10.)

Modified Condition Ratings	Unit 1	2	3	4	5	6
Generator	0,00	0,30	0,30	0,30	0,30	0,30
Transformer	0,25	0,25	0,00	0,25	0,25	0,25
Turbine	0,20	0,20	0,20	0,00	0,20	0,20
Governor	0,10	0,10	0,10	0,10	0,00	0,10
Exciter	0,10	0,00	0,10	0,10	0,10	0,10
Circuit Breaker	0,05	0,05	0,05	0,05	0,00	0,05
Unit Index	0,70	0,90	0,75	0,80	0,85	1,00
Station Index	0,83					

An example of investment planning using the HydroAMP Type 2 analysis is presented below:

Three plants are being evaluated for maintenance investment priorities. The components being examined are major power train components and a turbine hall crane. Priority criteria are in the following order: Priority Rank, Risk Map Score, and Condition Index. All factors previously mentioned in the analyses are presented for each component. Condition indexes are retrieved from Table 5. The yearly investment budget is 1 million USD. The final analysis provides the following results, detailed in Table 7: (Ibid. 20-21.)

Table 7. Type 2 analysis results (Bachmann et al. 21).

							Priority Focus:	(3)				(2)		(1)
Plant	Unit	Equipment	Investment Cost [k$]	Current Year Cost [k$]	Incremental Annual Maintenance [k$]	Achiev-ability	Phase	Condi-tion Index	Marginal Value of Generation [k$]	Total Outage Duration [a]	Revenue at Risk [k$]	Risk Map Score	Other Business Factors	Priority Rank
B	1	Generator 1	2500	1500	-50	H	P	2,9	600	2	1200	15	0	15
B	4	Transformer 4	800	500	-10	H	P	2,7	600	1,4	840	14	0	14
A	2	Transformer 2	800	500	-10	H	P	2,7	190	1,4	266	11	2	13
B	1	Transformer 1	800	500	-10	H	P	2,7	600	0,8	480	12	0	12
B		Crane 1	500	300	-20	H	S	5,3	0		0	5	4	9
C	3	Transformer 3	1000	100	-10	L	S	4,9	190	1,4	266	8	0	8
A	1	Transformer 1	1000	100	-10	M	S	5,2	190	1,4	266	7	0	7
B	1	Breaker 1	200	180	-15	H	S	5,0	600	0,4	240	7	0	7
C	2	Governor 2	200	180	-15	H	E	5,0	190	0,2	38	5	0	5
C	1	Breaker 1	200	20	-15	M	S	6,8	190	0,4	76	4	0	4
Total			8000	3880										

The equipment listed in Table 7 has been organized according to Priority Rank. The highest investment priority is given to Generator 1 at Plant B. However, its current year investment cost is higher than the annual investment budget, so the project cannot be undertaken at this time. The Generator 1 issue will have to be addressed separately in the near future, as it still presents a significant risk to the company with a Risk Map Score of 15. Next on the list is Transformer 4 at Plant B. Its current year investment cost is only 500 000 USD, so its project can be planned for this year. This leaves another 500 000 USD for other maintenance projects, and no other medium-high or high Risk Map Scores. There are still some components in poor condition, however, which could adversely affect revenues, so the remainder of the budget should be allocated to them. Transformer 1 at Plant B has a Risk Map Score of 12, while Transformer 2 at Plant A has a score of 11. (Ibid. 20-21.)

It should be noted that due to environmental factors Transformer 2 rises higher on the priority ranking, making it preferable for investment. Transformer 2 also has a higher revenue at risk value. The remaining 500 000 USD can be allocated to Transformer 2. If the annual investment budget was higher, for example 1,5 million USD, it would be possible to plan the maintenance of Generator 1 for this year. However, this would consume the entire investment budget. Instead, it would be preferable to invest in the maintenance of Transformers 4, 2 and 1, as together they represent more revenue at risk than the generator alone. There is also the added benefit of addressing the environmental problems associated with Transformer 2. (Ibid.)

Appendix III: EDF Example

A 600 MW coal-fired power plant fleet is made up of 3 units. The plants have recently been upgraded with air emission reduction systems that should allow them to operate up to 2030. The steam turbines are being evaluated for maintenance investment plans. During the SSC-elaboration it is discovered that a certain component C, that is part of the steam turbine, has the cumulative probability of failure shown in Figure 29. (Benetrix et al. 241.)

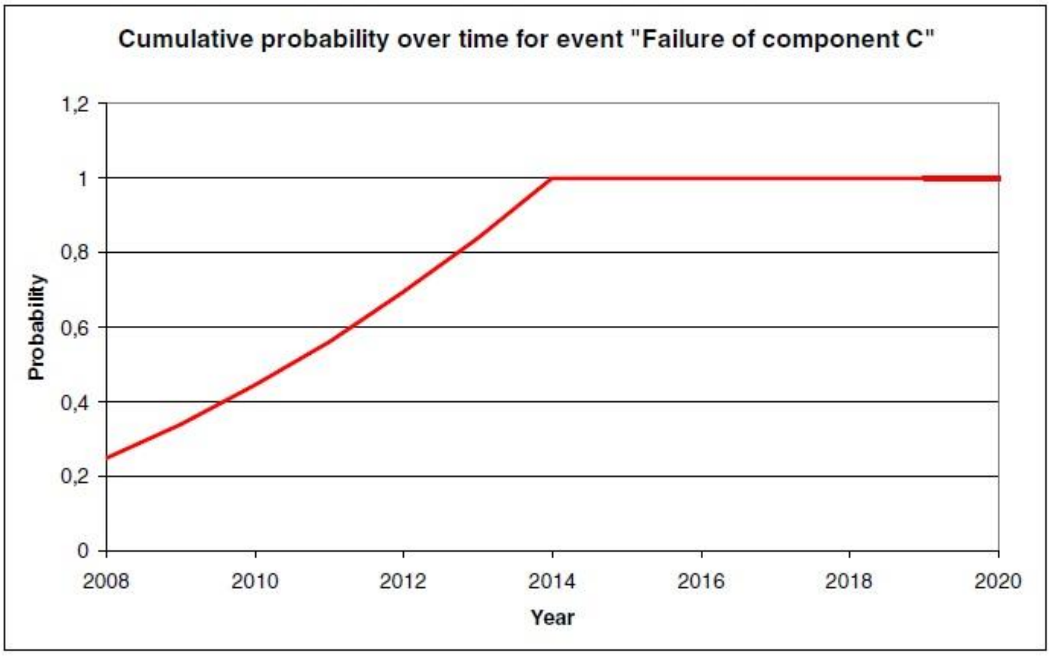

Figure 29. Failure probability of component C. Note that the study is done in 2009. (Benetrix et al. 241.)

The reference scenario for this component would be to initiate repairs every time the component fails. The repairs would incur a cost of X € and unavailability of Y weeks. After the repairs, the component failure probability is described in Figure 30. (Ibid.)

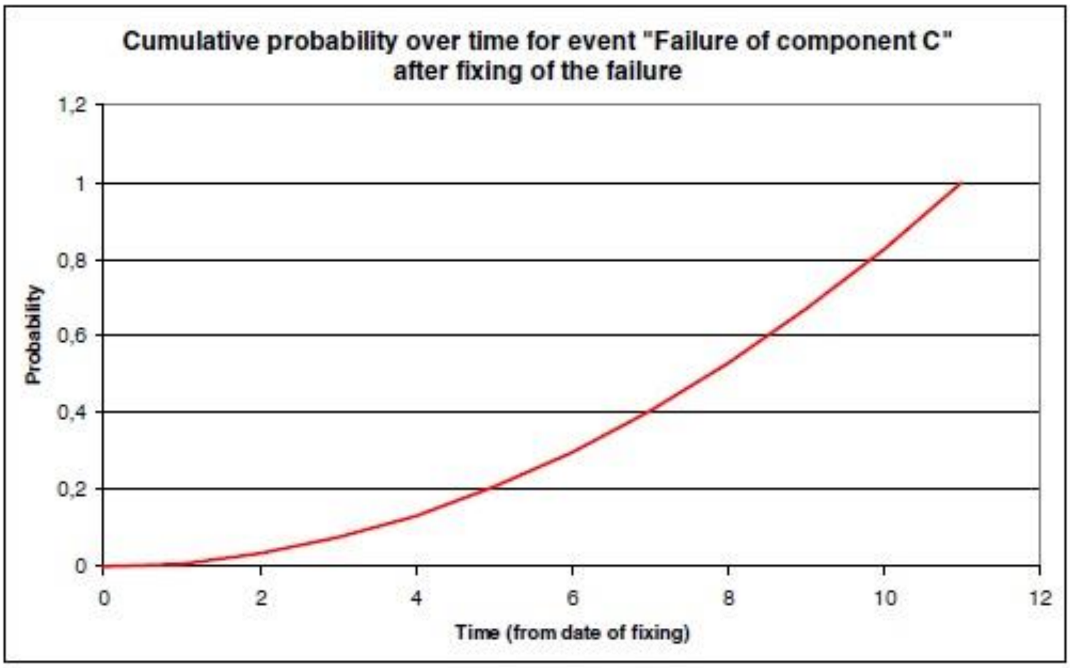

Figure 30. Probability of component C failure over time after repairs (Benetrix et al. 242).

An alternative scenario is created, where a new component C would be purchased in advance. The new component could then replace the old one once failure occurs. Purchasing a new component would be expensive; it would cost 4 times more than repairs. However, the replacement job will be cheaper than repairs and result in less plant unavailability. It is estimated that the new component, once installed, will last until the end of plant lifetime without further repairs. The old component can be fixed and used as a spare part for the other plants. The scenarios are summarized in Table 8. (Ibid.)

Table 8. Scenario summaries for component C (Benetrix et al. 242).

Reference Scenario		
Cause	**Mitigation actions**	**Probability after action**
Any occurrence of event "Failure of component C"	Fixing the failure: - X € - Y weeks unavailability	Figure 30
Alternative Scenario		
Date or occurrence	**Mitigation actions**	**Probability after action**
2010	Preventive aquisition of a new component C: - 4X € - 6Y weeks delivery	Unchanged
First occurrence of event "Failure of component C"	Replacement of component C with the new one: - 0,7X € - 0,35Y weeks unavailability	0 until end of plant life
First occurrence of event "Failure of component C"	Repairing the old component C: - X € - Y weeks delay without unavailability	Unchanged
Occurrence of event "Failure of component C" on other plants	Replacement of component C with the fixed one: - 0,7X € - 0,35 weeks unavailability	Figure 30

The NPV results are obtained computationally, and the evolution of the mean NPV can be seen in Figure 31. (Ibid. 243.)

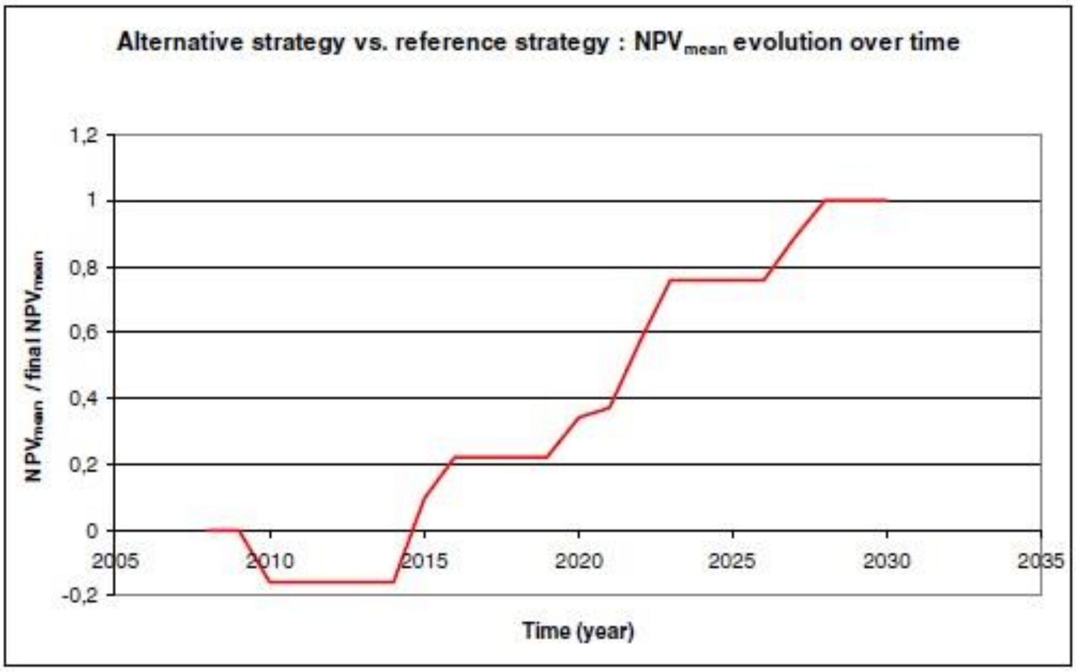

Figure 31. The evolution of the relative NPV of the alternative scenario compared to the reference scenario (Benetrix et al. 243).

From Figure 31 one can see that the alternative scenario is not preferable to the reference scenario early on, as the acquisition of the new component is quite expensive. Later on, however, the alternative scenario becomes more profitable as from 2015 and on the repeated failures and repair costs begin to accumulate. The acquisition of a spare part is profitable in the long term even though it is relatively expensive when compared to the corrective maintenance actions. This kind of SSC study will provide the decision maker with the information required to choose the optimal investment plan. (Ibid.)

Appendix IV: Westinghouse Example

The reliability improvement of buried pre-stressed concrete cylinder piping is evaluated. The system is assumed to have run at or near its design flow capacity and has been maintained fairly well. No design improvements, major repairs or replacements have been implemented during its service life. The base case strategy is the current maintenance plan, which includes cathodic protection (preventive maintenance), replacements and refurbishments (corrective maintenance) as determined by the current inspection program. The alternative strategies involve more extensive inspections, identification of significant degradation and repairs or reinforcements before failure. Alternative B uses acoustical emission and eddy current inspections to determine piping condition and implements repairs on significantly degraded sections, such as areas with fractured pre-stressing wires. Alternative C includes the actions taken in alternative B, but also adds the performance of a one-time carbonation testing and evaluates the need of special external coating for above-ground portions of the piping. The benefits of improved inspection methods and subsequent repairs are weighed against the costs incurred compared to the current run to failure maintenance plan. The results are displayed as probability density functions of the mean NPV change in Figures 32 and 33. (Sliter, 41, 129.)

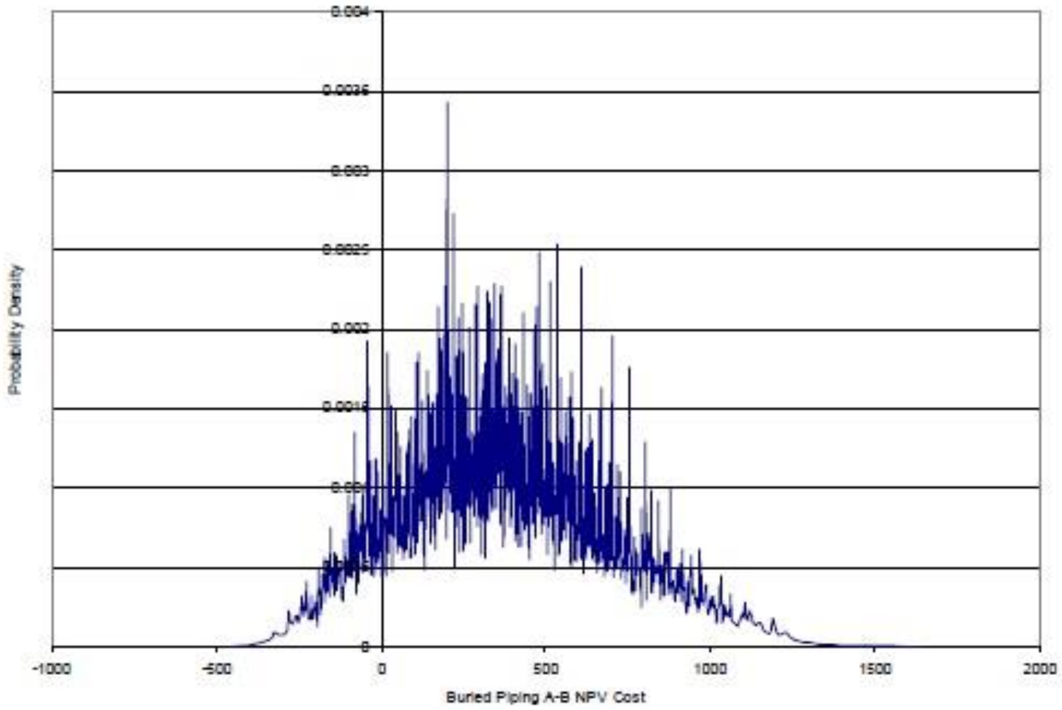

Figure 32. NPV change (k$) probability density of alternative B compared to base case A (Sliter, 133).

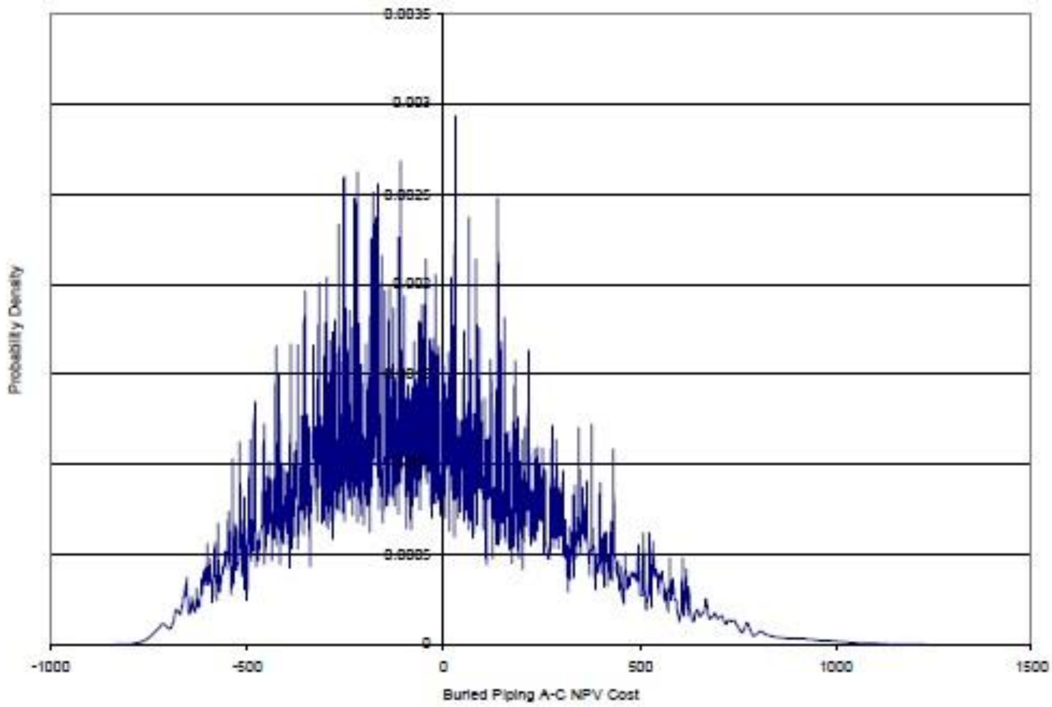

Figure 33. NPV change (k$) probability density of alternative C compared to base case A (Sliter, 135).

The positive NPV change indicates savings achieved from the alternative strategy. Negative NPV change, on the other hand, indicates increased costs from the alternative, meaning the base case would be more economically viable. The decision maker would have to look at two things from these figures. First, the optimal mean NPV change; which of the alternatives has the potential for highest cost savings. Second, the probability of regret, which is the probability that an alternative will be worse than the base case, that is which alternative has a larger probability of negative NPV change. From Figures 32 and 33, one can conclude that alternative B would be the optimal choice as it has a lower risk of negative NPV change and a higher positive NPV change than alternative C. (Ibid. 136-138.)