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APPLICATION NOTE

REPLACEMENT DECISIONS FOR AGEING PHYSICAL ASSETS

Ir. Martin van den Hout, Agidens Consulting

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Content provider(s)	Martin van den Hout
Author(s):	Martin van den Hout
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SUMMARY

Most organizations use physical assets for their activities. Physical assets are “things” such as machines, generators, buildings, cars or computers. There are many reasons why an organization could decide to replace an asset:

1. Changes in laws or regulations
2. Changed operational requirements, for instance if the market asks for a different product or more products
3. To take advantage of the benefits of new technology
4. Because an asset is no longer fit for use.

All of these aspects should be considered periodically in a standardized process when making decisions regarding investments in assets for the next one to ten year period.

The moment an asset will no longer be fit for use can seldom be determined when the asset is designed and put in place. It invariably depends upon criticality, operational conditions and environmental conditions. This is the reason there is a very large spread in useful asset life, even with the same type of assets within the same company.

Asset owners should periodically determine the remaining useful life (RUL) of their assets. An asset generally starts to deteriorate as it gets older. There are two main reasons why an organization needs to replace a deteriorated asset:

1. The operational costs, such as maintenance or energy costs, are rising to the point that it is economically better to invest in a new asset
2. The risk of critical failure is increasing to a level where it is no longer acceptable to use the asset

These are two different reasons that must be analyzed in two different ways.

A clear insight is necessary in the past and current costs of the asset, and in the age and condition of the asset, in order to correctly analyze the costs and to judge if replacement is economically a sound choice. This information is stored in an asset register. Based on past and current costs, it is possible to estimate with reasonable accuracy future costs. With this information in hand, it is possible to calculate the optimal moment of replacement.

It is not possible, however, to use only past data to judge if the risk of continuing to use an asset is acceptable. Some critical failures could have such a significant impact that an organization should avoid them at all cost. This means there are no (nor should there be) trends from the past. Obvious examples include the risk of an explosion or the risk of a system leaking and thereby causing major environmental pollution or risk to human life.

The following approach can be used to judge if these risks are growing over time and are still acceptable. First a methodology called ***criticality ranking*** is used to determine which assets could cause unacceptable failures. Once this ranking is determined, a ***failure mode and effect analysis (FMEA)*** is used to establish which causes could lead to these failures. Countermeasures and inspection programs can then be put in place to mitigate these risks and determine when an asset should be replaced.

TERMS AND DEFINITIONS

There are a great number of definitions used in standards and the literature regarding maintenance. The terms and definition in this chapter are principally based upon EN 13306 (2001): Maintenance Terminology and ISO55000 (2014): Asset Management.

Asset
An item, thing or entity that has potential or actual value to an organization (ISO55000).
A formally accountable item (ISO 13306).

Asset life
Period from asset creation to asset end-of-life.

Asset register
A list of the assets including all relevant technical and financial data.

Asset system
Set of assets that interact or are interrelated (ISO55000).

Cash Flow
The difference between money spent and money earned within a particular fiscal year.

Critical asset
Asset having the potential to significantly impact on the achievement of the organization’s objectives (ISO55000).

Critical failure
Failure with such severe consequences as to be considered unacceptable.

Failure
The inability of an item to perform a required function (ISO 13306).

Failure mode
Manner in which the inability of an item to perform a required function occurs.

Failure mechanism
Physical, chemical or other processes which lead or have led to failure.

Failure Mode and Effect Analysis (FMEA)
Systematic technique to analyze all potential failures—their causes, effects and consequences—of a system or process.

Item
Any part, component, device, subsystem, functional unit, equipment or system that can be considered individually.

Net Present Value (NPV)
Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows.

Maintenance
Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.

Operational Expenditure (OPEX)
Ongoing cost for running a product, business or system.

Organization
This includes any type of organization, ranging from a single person to a multinational corporation, a government institution or a nongovernmental organization (NGO). In this application note we use this term for any organization that wishes to implement the standards (ISO55000).

Preventive maintenance
Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item (ISO13306).

Asset replacement value(ARV)
The monetary cost of replacing the production capability of the present assets in a plant.

Remaining Useful Life (RUL)
The probable remaining time that the asset will be useful to the organization.

CONTEXT: WHY DOES IT MATTER?

Many asset systems in Europe are aging. A large part of our public infrastructure, such as electricity networks and sewer systems, was installed more than 40 years ago but was designed for a 30 year life expectancy. In a similar situation, many chemical plants were built in the 1960s and 1970s. They are already in use far longer than they were originally designed for.

All assets, including technical assets, deteriorate over time. That is just basic physics. Assets can also wear, corrode or age in sometimes less obvious ways. Maintenance can extend the useful life of asset systems, but there will almost certainly come a time when they should be replaced. So even if there are no overriding technical developments or new demands or laws, there can be two reasons for replacement:

1. The operational costs of the current asset systems have risen to a degree that it will cost less in the long-term to invest in a new asset system. There can be many reasons for operational costs to rise over the years. For example, macro-economic developments can lead to something as complex as labor relations in the form of increasing salary demands by operators or something as simple as the rise in energy prices. Technical deterioration can lead to increased maintenance costs or higher energy consumption or unavailability cost (value of lost production).
2. Because of asset system deterioration, the risks related to its operation can become unacceptable high. For instance, as piping systems get older, the risks of leakages may increase. In some cases this could lead to chemical spills causing a major environmental catastrophe. In other cases, undetected corrosion may cause weakening of metal parts that lead to the collapse of a steel structure. Until that moment the costs of maintenance or energy may not have been rising at all.

Even if the asset systems still seem to be in good working order, there may be other reasons for replacement. Such reasons can include changing requirements for an asset system, new laws and regulations or the introduction of new, better and more efficient technology.

The question of when asset systems should be replaced present big challenges for asset owners in Europe, even when the requirements, laws or technology have not changed. Asset owners must determine when asset systems are no longer appropriate for use from an economic or risk point of view as well. How much time an asset system can remain operational is called the Remaining Useful Life (RUL).

There are presently more than 10 million kilometers of power lines in Europe (Eurelectric, 2013). The sewage systems, water networks and other networks are of similar size. Replacing all asset systems older than 30 years would require enormous investments. It is often assumed that replacement is not necessary, because the asset systems are still running. Many knowledgeable individuals fear, however, that such ageing asset systems may suddenly fail or cause major catastrophes at some point. Investment decisions however should not be based on solely on feelings and fears but rather on a rational analytical approach of costs and risks.

A structured method to determine the RUL of asset systems is necessary to calculate and plan the necessary investments over the coming decades. If investments are made too early, it is a waste of RUL. If investments are carried out too late, the operational costs (OPEX) and risks involved in operating systems will become too onerous.

This is a very important, albeit delicate balance. In many organizations, the capital costs make up fifty percent of all operational costs. The capital costs are the interest and depreciation of asset systems that were installed in the past. Careful planning over the long-term is necessary because the asset replacement value (ARV) of many asset systems is so high. Astute asset owners plan further ahead than the next three to five years. The scale of an investment requires longer term planning. Investing too little now, may lead to major investment needs ten years from now.

Remaining Useful Life (RUL)

One common misunderstanding about the useful life of asset systems is that asset systems only reach a replacement point when they fail or when they have to be replaced for some other reason. Many asset systems can, in principle, be kept running eternally, provided they receive proper maintenance and replacement parts.

Even if an asset deteriorates by failure mechanisms that will always result in it having a limited useful life, the spread in life expectancy between assets of the same type can be huge. It is very expensive and dangerous to assume a fixed life for each type of asset. This can be especially true of an electromotor rated to run for 100,000 hours, an electrical cable rated last 20 years or a vehicle intended to be run for 200,000 kilometers. Some vehicles may need replacement after only 100,000 kilometers while others will operate for 500,000 kilometers. In the same way, some pipelines can last hundreds of years, while others will be deteriorated after just a few years.

There are many factors influencing the life of the asset. The most important are:

1. Quality of the components
2. Quality of the way the components are assembled
3. Load on the asset (load/strength ratio)
4. Chemical influences
5. Working conditions such as temperature or vibration
6. Raw material used in the process

To give a few examples:

- The strength of the electrical field has a huge impact on the life of polyethylene insulation of cables. Tinga (Tinga, 2013) for instance describes that an electrical field that is twice as strong decreases lifespan by 500 times!
- The life of an electromotor will be three times as short if the motor is not perfectly aligned at its coupling.
- An increase of the mechanical tension on the ball of a ball bearing of 10% can reduce the life of the bearing by 75%.

This all means that even if two assets are identical and seemingly working under identical circumstances, the Remaining Useful Life (RUL) may be completely different and can never be taken for granted. Although calculating an average is possible, calculating the life of a particular asset in a particular environment is not.

GENERAL APPROACH

In general, asset owners have several options:

1. Keeping their current asset systems up and running according to all standards for production and safety. This may well cost more and elevate maintenance and energy costs as asset systems age
2. Replace all assets with new assets. This requires an enormous investment
3. Do nothing: wait and see what happens. This will lead to high corrective costs, low availability and to possibly major accidents.
4. Use a balanced asset management approach to find the balance between operational expenses (OPEX), investments (CAPEX) and risk.

It is obvious this fourth approach is the only sensible one. This application note describes the steps necessary for this way of working. It consists of the following:

- Setting up a team for the project
- Setting up the asset register
- Analyzing the costs and determining the Remaining Useful Life (RUL) from a cost perspective
- Analyzing the risks and determining the RUL from a risk perspective
- Keeping the system up to date

The next chapters will provide details of each of these topics.

First the document will go a bit deeper into the reasons for replacing asset systems.

Reasons for replacing asset systems

There are several reasons to replace asset systems that are currently in use:

1. The end of the useful life. This depends on a number of factors. When an asset system ages, its operational costs may rise. The costs of corrective maintenance can increase and more and more preventive maintenance may become necessary to keep the asset system operational. Some asset systems may also use more energy as they get older, because leakages, wear or increase friction. Even if the costs do not rise, it may be necessary to replace an asset system, because of increased risks. These risks can be of many different types. A failure of equipment can lead to casualties if for instance an asset system explodes. But very long interruptions in the availability of the asset system can be a reason for replacement as well. Another consideration is that when an old asset fails it can be very hard or even impossible to repair for a number of reasons. This can cause very long delays.
2. Changing requirements. Many companies and organizations are working in an ever-changing market. Some try to keep supplying this market with their existing assets. Sometimes this can be done. However, it may lead to misusing assets for a purpose they were not designed for. Changing asset systems too often leads to major investments and time lost because of start-up problems. Not changing assets often enough leads to loss of efficiency and quality, and higher operational costs.
3. To comply with legal demands (safety, environmental, or other). In many cases, new laws do not apply to existing equipment. In some cases however, stricter regulations for safety, energy consumption, customer safety or other rules make replacement of an asset system obligatory.
4. Technical developments. Newer asset systems can be faster, more reliable, deliver better quality and use less energy. Even if the old equipment is still working fine, it may be better to replace it.

The last three reasons very strongly dependent upon the specific type of asset system and organization under consideration. They are out of the scope of this application note. It is however important to include them in the process of decision making.

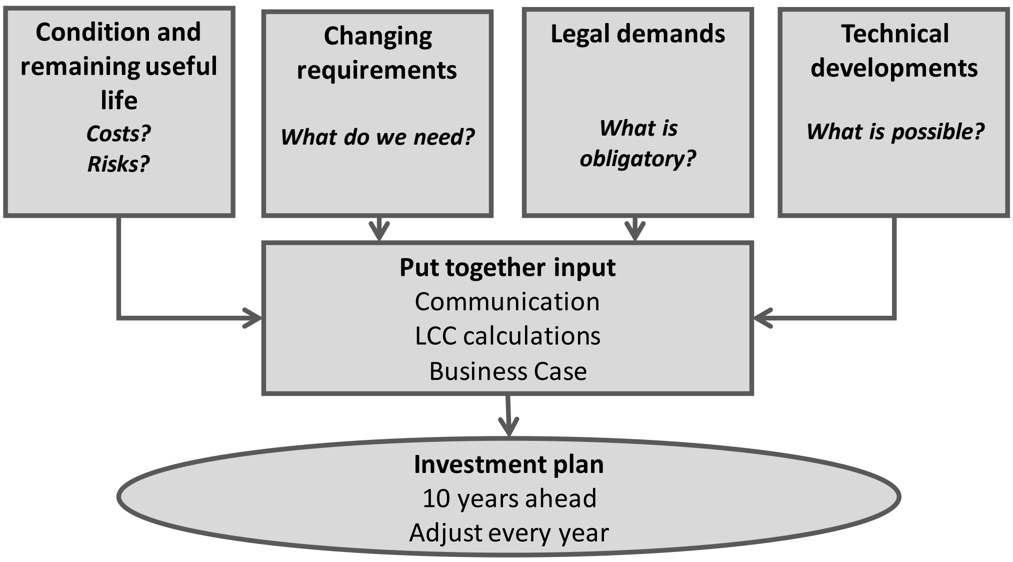

Figure 1 – The main outline of the decision making process.

The four blocks in the top of the figure show the reasons for replacement of an asset system. Only the innovation for technical developments is in general seen as an opportunity. An organization can choose to take it or leave it. The other three reasons make replacement of the asset system necessary. At some point the organization has no other choice if it is to remain viable.

SETTING UP A PROJECT FOR ASSESSING THE RUL

All input to decide on replacement of asset systems (see figure 1) must be communicated among all relevant departments and recorded in a central asset register in order to maintain an integrated overview. The organization can then develop an investment plan based on all of the applicable input. This needs to be planned at least five to ten years in advance, especially if large numbers of assets are involved.

This application note only describes how an organization can determine the Remaining Useful Life, which is crucial input for the investment plan (see figure 1).

SETTING UP A PROJECT TEAM

Determining the RUL and necessary investments for the next ten years requires a team effort. The input of many fields of expertise is necessary. A team could consist of experts from:

1. Operations: to determine the impact of failures and downtime of equipment on the business output of the organization
2. Maintenance and Reliability: to predict how the costs for preventive maintenance and the costs for corrective maintenance and involved risks will evolve in the future
3. Safety and Environmental: to determine the impact of asset failure
4. Engineering: to determine the best option for replacement and the associated investment needs
5. Finance: to determine the asset values and develop the investment plans
6. Marketing: to provide input about future market needs
7. R&D: to give input about new technological developments
8. Management: to decide on the strategy of the organization and make available the necessary resources

THE ASSET REGISTER

An organization must have clear overview of the assets it is using if it is to be able to make good replacement decisions or optimally manage asset systems. This overview is called an asset register. It contains information on the assets and their relevant characteristics, such as:

1. Their exact location. If the system is for instance a network of electricity cables in a country where the cables are buried in the ground, the power company must know the exact locations. This information is necessary for many activities, for instance if an inspection must be performed.
2. Technical characteristics, such as type, size or material
3. The age of the assets
4. Their failure behavior
5. Operating environment of an item and load characteristics

The organization needs to record and analyze the following parameters for each asset in the asset register or asset system:

1. The Operational Expenditure (OPEX) per period
2. Preventive maintenance costs
3. Corrective maintenance costs
4. Energy costs
5. Preventive maintenance history
6. Which corrective maintenance has been executed in the past
7. Which modifications have been applied to the asset and why
8. Asset replacement value

9. Remaining capital costs if any
10. Unavailability cost (production losses)

The information summarized above can be managed in an Enterprise Asset Management (EAM) system. One of the problems in many organizations is that they manage several computerized systems, such as:

1. An EAM
2. An financial accounting system
3. A geographical information system (GIS)

These systems often contain contradictory information regarding the same asset. When looking at the financial systems of a company, one might conclude that most assets data back to the 1990s, while the EAM gives the impression most assets are less than five years old.

Gathering, cleaning and consolidating all data can be a very time consuming job. It is important that once this job is done and the model is developed, it is managed well and updated regularly.

COSTS

The two most important reasons why an asset is no longer fit for use are (as was mentioned earlier):

1. The operational costs (maintenance, energy, downtime, et cetera) are rising and it is more economical to replace the asset with a new one with lower operating costs.
2. The risks associated with using the asset increase as the asset ages.

These two reasons require two types of analysis to determine the optimal moment for replacement of an asset. From cost perspective, it is necessary to calculate and predict the total operational costs per year.

In the first few years it is normal that very few components fail. Although there is usually a higher failure rate in the initial period of use, after a run in period, components of the asset usually function without major issues for many years. They typically start to fail or need preventive replacement later in their life cycle. This creates the need for preventive maintenance, and accounts for the increased number of failures, rising maintenance costs and increased downtime. As time goes by, more and more components can be expected to fail.

Often, the failure or degradation of one component influences the failure frequency of other components as well. Worn electrical components may generate heat that causes the temperature of other components in their surroundings to rise. Other components may exhibit accelerated aging because of this excess heat. If the main guide bushes and shafts of a mechanical machine get more clearance through wear, the machine starts to vibrate more and this also has a negative impact on the life and energy use of the equipment.

Not only do worn components influence the RUL of other components, they can also profoundly affect energy use. When the time comes that major parts of the asset need replacement, such as a frame, a vessel or numerous cables within an infrastructure network, it may be better to replace the asset as a whole, rather than simply replace a few obvious components.

Many organizations focus on the reliability of equipment when they make replacement decisions. While the energy consumption is also a major factor to consider, it often gets less attention, because it does not directly influence the day to day operations of an organization. The energy invoice is sent to the accounting department and paid for, without any other department being advised.

Energy consumption is especially important when a decision has to be made between replacing and overhauling an asset. Many modern assets consume less energy than their equivalents of ten or twenty years ago. For instance, an electric motor of 10 KW of efficiency class IE1 has an efficiency of 87%, while a motor of efficiency class IE4 has an efficiency of 93%. On average the best available motors will save about 5% of electrical energy. Combining them with the better designed electromechanical systems can lead to another 25% saving. That is obviously a significant figure and is often overlooked since energy is usually invoiced based on overall plant use and is not an itemized cost by asset in operations.

Organizations should develop standards to ensure that the most energy efficient option is selected when maintenance or engineering decisions are made. This will become far more important in the future as fossil energy sources run out and CO_2 concentrations in the atmosphere continue to rise.

In the European Union alone, roughly 25,000,000 electrical motors are sold every year. Implementing the better systems worldwide, would lead to an estimated energy saving by 2030 of 322 TWh, saving about 206 Mt of CO2 emissions (Waide & Brunner).

COST ANALYSIS

Figure 2 shows an example of the maintenance costs and energy costs of *asset x* over a period of 51 years. For the purpose of simplicity, in this document we consider the costs of downtime caused by breakdowns as maintenance costs. They must however not be neglected, because for many asset systems the costs of production loss during a breakdown is much higher than the actual costs of repair.

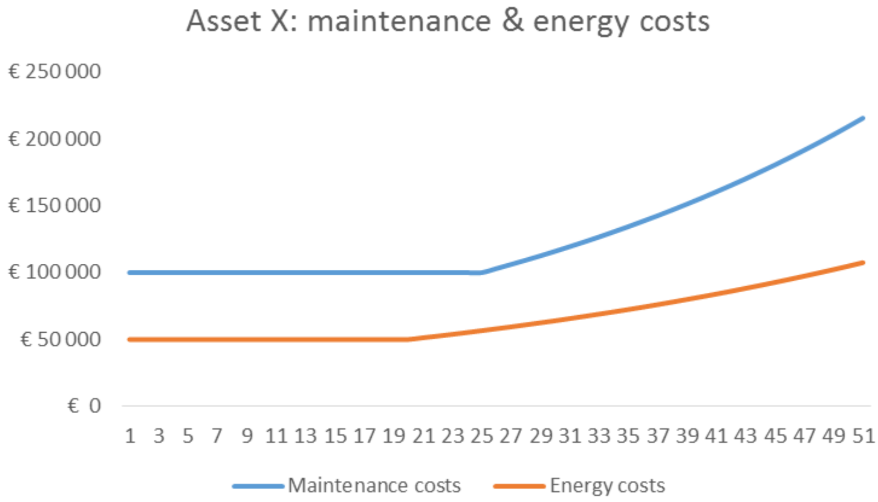

Figure 2

After approximately twenty years of use, the asset is starting to deteriorate significantly. There is a commensurate rise in the cost of maintenance and energy use for this asset. It is clear that if this trend continues, the costs will become so high that it would be better to replace the asset. To obtain the optimum replacement point, all operational costs have to be weighed against the cost of investing in another identical—or what is more likely—a new more efficient asset. For the purpose of simplicity of this example, we presume that all other operational expenditures (OPEX) – such as labor costs – are stable over the years.

The most important costs of investment are the costs of capital: depreciation and interest. For asset x, we presume it is depreciated over a period of 10 years. Figure 3 shows the annual costs of capital for asset x.

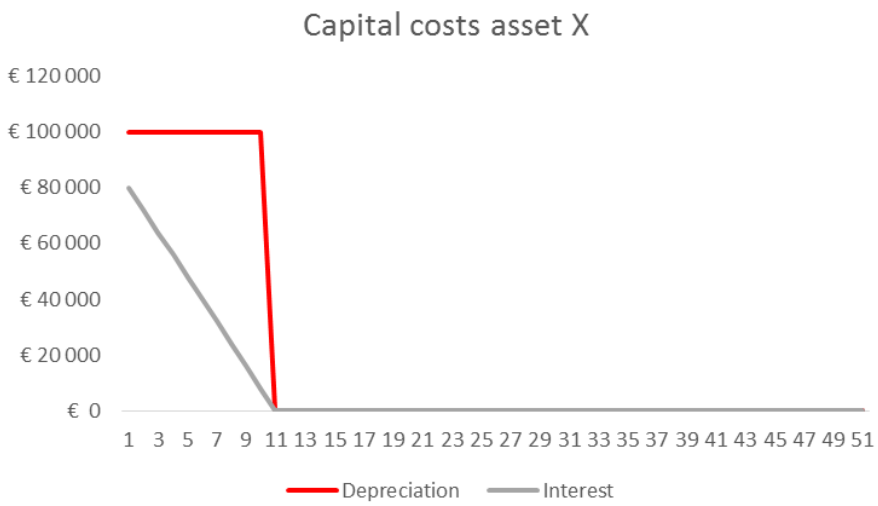

Figure 3

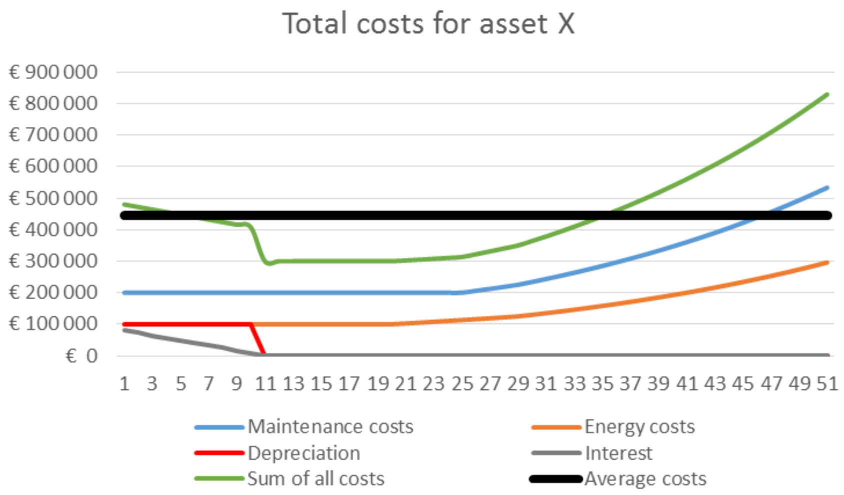

Figure 4

The green line in this figure shows the total of all costs. The thick black horizontal line shows the average total costs per year during the period under consideration. So this is the cost level that results if all costs are added up over the life of the asset and divided by its age (in years). It is these total average costs per year that need to be minimized. One of the ways to do this is to calculate the Equivalent Annual Costs (EAC), which will be explained later.

If an asset is replaced too early, the capital costs will be too high over the period. If the asset is replaced too late, the operational costs are too high.

If all costs, now and in the future, are known, it is possible to calculate the optimal moment for replacement of the asset.

Of course, we can never know the future maintenance costs of an asset with any exactitude, but there are ways to make a confident prediction:

1. Using standard tables with historical data of components. This is not very accurate, because the failure rate of a component strongly depends on its quality, its application, and the operational circumstances in which it is being used. However if an organization has many similar assets, this method can provide some useful data.
2. Using historical data of the actual component on site. Weibull analysis can be used to extrapolate historical data to the future. This method requires very little data in order to make a quite reliable prediction of future failure behavior of an asset.
3. Using expert opinions.

To be able to calculate the optimal moment for replacement, we have to take into account financial inflation and interest rates.

An organization prefers to have one thousand euros today to having one thousand euros a year from now or ten years from now. The investment in new assets is carried out at a certain moment and should pay itself back over a period of years. To make a good calculation, future costs and benefits have to be calculated back to present day value.

To do this the Net Present Value (NPV) formula is used:

$$NPV = CF/(1+R)^y$$

With CF = cash flow

R = Interest

y = Year (1, 2, 3, …)

The Cash Flow is the difference between money spent and money earned in a given year. This can include anticipated costs of maintenance, personnel or energy five years or ten years from now. Suppose the calculation is made to calculate the NPV of a cash flow of € 100,000, ten years from now. If the company has an interest rate of 8%, then the formula becomes:

$$€\ 100{,}000/(1+0.08)^{10} = €\ 46{,}319.35$$

So at an interest rate of 8%, it is the same for the organization if it possesses € 46,319.35 now or € 100,000 ten years from now. This calculation must be made for the cash flows in every separate year in the future.

To calculate the real NPV for an investment, the sum of all the NPVs for every year over the life cycle of the asset system must be calculated, minus the initial investment amount.

The NPV can be used to calculate the Equivalent Annual Cost (EAC). The EAC is the actual cost per year, calculated back to the value of money in the present year. The EAC is calculated by dividing the NPV of an asset by the annuity factor.

$$EAC = NPV/A(t,R)$$

With $A(t,R) = (1 - 1/(1+R)^t)/R$

This formula can be used to calculate the EAC for different scenarios, such as keeping the present asset in use for another five years versus keeping the present asset in use for another ten years or installing new assets immediately. This formula can be used as well if the different options for new assets have different life expectancies. By comparing the outcomes of the calculations, the option with the lowest EAC can be chosen.

The most difficult part in these assessments is collecting the accurate data for the calculations. Therefore it is important to set up an effective enterprise asset management database to collect all of the relevant technical and financial data regarding the assets. Many organizations do not have an effective system or they only have data going back a few years. This might not be enough to enable the accurate identification of a trend in costs.

In case there are not enough data to make a calculation, it is possible to estimate data based on expert opinion. There are some software tools that can create future cost patterns based on wizards that ask concrete questions that the people using or maintaining the system can fill in. Often the help of a consultant is needed to assure the validity of the data.

RISK

The increasing risks of failure can be a reason for replacement quite apart from increasing operational costs. In the previous paragraph the optimal moment for replacement was determined by looking at the trends of costs. When considering risks, it is not possible to look at trends. Some failures may have such severe consequences that they must not be allowed to happen even once. Therefore statistics of the failures of the asset in the past should never be used as an indication for future behavior. The analysis of risks requires the following, different approach:

1. Determine the level of risk that the organization is willing to accept
2. Determine which assets could in principle fail with unacceptable consequences
3. Perform a risk analysis, for example a FMEA, to establish which failure modes could lead to these critical failures. In this document the term ***critical failures*** means those failures which must never be allowed to happen even once (such as severe safety accidents or environmental incidents).
4. Carry out inspections on the actual assets to determine their condition

THE LEVEL OF RISK AN ORGANIZATION IS WILLING TO ACCEPT

The senior management must state clearly what level of risk it is willing to accept. No operation can ever be 100% risk free. There is always a chance that something will fail. Failures can have consequences in many areas, such as:

- Safety
- Environment
- Quality
- Reliability of delivery
- Unavailability of production equipment
- Labor circumstances
- Security
- Legal requirements
- Corporate image
- Comfort
- Politics

Of course not every one of these aspects is relevant to every organization. To visualize what level of risk the senior management is willing to accept, a risk matrix is set up. It shows the relation between the severity and the frequency of incidents.

Severity	Economics	Safety	Quality	< 1 time/ 50 years	< 1 time/ 10 years	< 1 time/ year	< 1 time / month	> 1 time/ month
1	<€ 1000	No impact	No impact					
2	<€ 5000	First Aid	Minor complaint					
3	<€ 50.000	Lost time incident	Customer return					
4	<€ 500.000	Permanent disabled						
5	> € 500.000	Death	Product recall					

Figure 5 – Example of a risk matrix.

The first column of this matrix gives a ranking of 1 to 5 for the impact severity of incidents. The next three columns define the severity categories, in this case by the impact on cost, safety and quality. The following columns indicate how often a certain failure is allowed to happen. A green block means the failure is acceptable. An orange means improvement needs to be planned. Red means the failure is unacceptable and immediate action is necessary. For example: an organization determines that a power failure of longer than four hours will occur less than once every ten years and has a severity score of 3. This means no action is needed.

Some organizations also use the risk matrix for:

- Decisions on preventive maintenance
- Decisions on counter measures after incidents
- Designing new asset systems

How to select the critical equipment

It is not necessary to do a detailed analysis of each asset and list all possible failure modes. This analysis only needs to be done for assets that can lead to unacceptable risks according to the risk matrix.

A criticality ranking should be carried out to determine which assets these are applicable to. The result of the criticality ranking provides an overview of the impact of potential failures on each of the aspects, such as safety or the environment. This list clearly shows which assets might have unacceptable failures. This list can also be used for purposes other than for determining the RUL, e.g. to set up preventive maintenance. The results of the criticality ranking should be kept with the asset register for future use.

Criticality ranking is performed by a team of specialists with an in-depth knowledge of the assets under investigation. The team is led by a facilitator who is familiar with the methodology and keeps a record of the results.

The team discusses what would be the worst impact that each asset could realistically have on the criteria that are included in the risk matrix. For example, if failure of an asset could lead to a fatality, but have no financial impact or no impact on quality, it would score 1 for Economics, 5 for Safety and 1 for Quality in the matrix above.

This methodology enables the team to determine which equipment is likely to pose unacceptable threats to the business strategy of the organization. Only these assets need to be investigated further to determine if the risk of an unacceptable failure is increasing and becoming unacceptable.

There is a crucial difference between cost analysis and risk analysis: in principal all assets need to be analyzed to establish their optimal economic replacement interval, but only the critical assets need to be assessed to determine if the risk of failure is acceptable.

Failure Mode and Effect Analysis for the critical equipment

It is necessary to proactively analyze what risks are present for the critical equipment and then to determine if they are under appropriate levels of control. It is necessary to analyze which failures could have an unacceptable impact on the criteria from the risk matrix, such as safety or the environment. A Failure Mode and Effect Analysis (FMEA) can be performed to determine which failures could occur.

A FMEA should be carried out by team of people that know the asset with a variety of different points of view. In industry these typical are:

1. An engineer who knows how the asset is designed and how it should function
2. A reliability engineer who knows the most common failures, the current maintenance plan and the relation between failures and age.
3. A process engineer who knows the relationships within the entire process
4. A production manager or engineer who knows the impact of failure on operations

The team is led by a facilitator.

The result of this FMEA is a clear list of all failures that could occur in the critical assets. This list is the input for the next step: an analysis to determine if the organization has the risks of these failures well enough under control and if investments are necessary in the foreseeable future to eliminate these risks.

Many different failures can occur to each separate asset. For a complete industrial plant, these can add up to hundreds of thousands of failures. Because of this:

1. It is important to do a good criticality ranking, so that the team can focus its attention on the right assets.
2. The FMEA is carried out as thoroughly as is required by the criticality of the asset. Making a list of all possible failures is not necessary in most cases. Covering the most frequent or severe failures is enough. Failures that do not have severe consequences do not need to be analyzed as thoroughly. A sensible approach is required for the use of the FMEA.

During an FMEA, the team answers the following questions:

1. What are the functional demands for the asset?
2. Which failures can occur?
3. Which causes can lead to these failures?
4. What is the effect of these failures, i.e. what actually happens?
5. What are the consequences of the failures? Why does it matter?

FUNCTIONAL DEMANDS

In order to determine how an asset may fail, we must first define what we mean by failure. A failure is the termination of the ability of an item to perform a required function. Therefore it is crucial to first clearly define the required function.

Let’s take the example of a transformer. Its job is to transform the voltage of an electrical current to another level. If it does not produce the proper voltage or if it does not conduct the current at all, it has failed. This is obvious. However, a transformer will also lose some of its energy-efficiency over time. It is not necessary or economically optimal to keep every transformer at maximum energy efficiency. The team will have to specify how much loss of energy efficiency is acceptable to still comply with the demands senior management has set.

Another example is paintwork. If the organization specifies aesthetic demands for the paintwork (i.e. it should look good), a different interval between paint jobs is necessary than when the paintwork only has to preserve the material that is painted, but it doesn’t have to look brand new.

A division must be made between primary and secondary demands. The primary demands are related to the function for which the equipment was purchased. The transformer should be able to transform a certain amount of electrical power from X volts to Y volts. Secondary demands are the extra features that are required from the asset. Examples include energy consumption, safety, quality, environmental demands, or aesthetics. The division between primary and secondary demands does not express any priority of one over the other; it is rather a methodology to avoid a situation where secondary demands are ignored or overlooked entirely.

(FUNCTIONAL) FAILURES

The second step in the FMEA is to establish all failures. The functional failures follow logically from the functional demands. Suppose for example the demand for a transformer is to transform a certain amount of electrical power from a high voltage to 400V +/- 5%. The secondary demands are that it should be safe (avoiding equipment damage and human injuries) and its energy efficiency should be higher than 98%. In this case the failure modes can be:

1. The transformer cannot transform enough power
2. It cannot transform power at all
3. The output voltage is higher than 420V
4. The output voltage is lower than 380V
5. It's efficiency is lower than 98%
6. It is unsafe

A functional failure is not a cause. It is just a description of what can go wrong. It is very important to have a clear list of all functional failures. In the next step, the team will investigate potential causes for each functional failure, one by one. The causes of the failure, for instance "the output voltage is higher than 420 volts", may be different than the causes of the failure "the output current is lower than 380 volts".

FAILURE CAUSES

In this step, the team begins its analysis of all possible causes of the potential functional failures that it listed in the previous step. This listing of the failure causes is the most time consuming step of the analysis. It is not necessary to develop inventories for all failure modes in order to make a remaining life analysis. The FMEA should only focus on failures that have unacceptable consequences (as stipulated in the risk matrix).

In most cases, only a short list of failures remains; namely the ones that relate to:

1. The integrity of main structures, infrastructure and vessels
2. Obsolescence of control equipment

It is necessary to find the causes behind the causes, until the description of a cause is specific enough that a counter measure can be selected. A cause of failure on an electromotor may be for instance a short circuit in its windings. It is very hard to determine which preventive maintenance actions can prevent this from happening. There can be many causes leading to the short circuit. One of the causes may be damage to the insulation. This may again be caused by overheating of the motor, which in its turn may be caused by too high of an ambient temperature, by electrical overload, by a broken cooling fan, or by dust on the outside of the motor. The team should take the analysis down to this fine level of detail, before it can determine:

1. If an inspection method is possible to establish the condition of the asset
2. If the useful life can be predicted based on experiences with similar failures in similar equipment
3. If the life of the asset can be made longer by appropriate measures (e.g. cooling of the motor)

FAILURE EFFECT

A failure effect describes exactly what is happening when the failure occurs. Effects can be macro or micro. Macro effects are the scenario of what happens when the failure occurs. If for instance the electrical motor fails, a cooling pump stops running and an alarm sounds in the control room. Micro effects describe local events inside the concerned device or directly related to it. Dust gathers on the motor; this can be seen. Slowly the temperature of the motor rises; this could be detected. Subsequently, the resistance of the windings starts to drop and eventually the motor fails.

Macro effects describe the events that happen outside of the concerned device. They lead directly to the failure consequences. The micro effects give an indication of how a failure can be detected before it occurs.

Failure consequences

A failure consequence precisely describes the impact of the failure. Is safety at risk? Is the environment threatened with pollution? Does the organization lose money? If a failure has no severe consequences and it will require significant resources to prevent it, prevention may not be desirable from an economic standpoint.

In an FMEA, the consequences of failures are rated on a scale of 1 to 10 for:

1. Severity: what is the impact if failure occurs?
2. Occurrence: what is the chance of the failure happening?
3. Detectability: if the failure occurs, how long will it take before somebody notices it?

By multiplying the score for each aspect a Risk Priority Number (RPN) is found, ranging from 1 to 1,000.

Compensating provisions

The next step in a standard FMEA would be to determine compensation provisions or counter measures to reduce the risk of a failure. Several different types of counter measures are possible, including among others:

1. Technical modification of the asset
2. Change of operating procedure
3. Training of operators
4. Installing alarms and other protective devices
5. Condition monitoring, or visual inspection
6. Periodic exchange of components

These counter measures can have a significant positive influence on both risks and costs. For many of the aging assets, it is not unusual to discover that some or even all of these counter measures have already been implemented through the years. The purpose of the remaining life analysis is to investigate the failure modes that are:

1. Age related, such as corrosion, fatigue, wear, et cetera
2. Are not detected during the already existing periodic inspections. In production machines, the most important wear and corrosion items are often already under scrutiny. This is different for large infrastructure systems and process plants. Often these suffer from aging processes that are hard to detect because they require a great deal of effort to detect and the organization does not have the resources to frequently inspect them all. In most cases these inspections require a shutdown of the asset system. This can be costly in both financial and effort terms in large systems. Therefore a well-balanced inspection program is needed.

Inspection in the field

Once a clear list of all possible critical failures is established, it is possible to determine the remaining useful life per failure. It is a common misunderstanding that it is always possible to calculate the life of an asset during the design stage. This is seldom the case. Only ten to twenty percent of all failure causes are age related. Even for age related failures, the life of the asset is strongly influenced by numerous factors such as:

1. Load on the asset
2. Temperature
3. Quality of the components
4. Quality of the assembly

In practice, the best and only realistic approach to determine the remaining useful life is to implement an inspection program that examines the condition of the asset on a regular base, based on the results of the FMEA. This means the inspection is targeted on specific points, such as the wall thickness of a vessel, the insulation quality of a cable, et cetera.

Based on the inspection results of each individual asset, an estimate is made of the remaining useful life.

The inspection should be repeated on a regular base. The interval between inspections depends on the physical or chemical mechanism that causes the degeneration. An inspection interval of 5 to 10 years is sufficient for most failure mechanisms leading to aging.

One common problem is that an organization has too many assets to inspect them all on a regular base. If an electrical power supplier has for instance 20,000 kilometers of cabling in its network, it is unlikely they will be able to inspect all cables every five years. In this case a priority is set, based upon:

1. The criticality of each cable
2. The working conditions of the cables
3. The age of each cable

To put it more concretely for the above example, cable criticality is determined based on its ranking. A subsequent analysis must be made of the crucial working conditions and environmental conditions such as soil type for underground cables, environmental temperatures and cable load.

An interesting new development in this area is the application of data sciences on asset data.

Many asset owners have huge amount of data regarding their assets. They are kept in all kinds of different databases and other systems. Data mining techniques enable the combining of this information into the asset register. This database can contain information such as:

1. Precisely which assets does the organization own? Is it really 20,000 kilometers of cable or 21,000?
2. Where are they located?
3. In what type of soil are the cables buried?
4. What is their exact specification, diameter, insulation material, et cetera?
5. How many failures occur each year at each location?
6. What are the maintenance costs of each soil type, environment, et cetera?

Correlations can be found based on these data. The analysis may show that cables with insulation material X in sandy soil have costs of Y euro per kilometer after 30 years and Z euro per kilometer after 40 years.
Because the database also shows how many kilometers of cable are in each category, more accurate predictions can be made about future costs.

Keeping the system up to date

Making investment decisions requires a standard process, based on solid data. This means first and foremost that all the data must be kept up to date.

The previous paragraph described the asset register, which contained all relevant financial and technical data about the assets of the organization.

The organization needs several processes to guarantee that this register is continuously kept up to date.

The first of these required processes is a management of change process which describes how the data in the asset register should be updated after each change in the assets or investment in new assets. Updating the asset register should also be a part of the financial and technical process for repairs and preventive maintenance.

Only in this way can the organization be certain that the correct data are present in the asset register.

Often organizations lack the procedures or the discipline to keep their data up to date. If the data in the register cannot be trusted, then the organization will have to spend a lot of effort in gathering, checking and cleaning the database.

Once an organization is certain it has correct and complete data, it should review the analysis described in this application note every year. It should review:

1. The criticality ranking—to verify any changes in criticality
2. Trends in maintenance and energy costs to fine-tune and adjust the predictions
3. The FMEA to verify if there are any changes in the process or conditions that could lead to new failures or causes
4. Inspection results—to determine if the deterioration of critical assets is serious enough to plan replacement

All of this information about the remaining useful life should be combined with information about:

1. New laws and regulations
2. New technologies
3. New business demands

Based on the totality of all of this information, an investment plan with a high level of confidence can be developed describing the probable investments for the next ten years in general terms and for the next year in greater detail.

CONCLUSIONS

Many assets in European infrastructure and industry are older than the life they were originally designed for. Replacing them would require enormous investments and is often not necessary. However in some cases, failure to replace them may lead to high energy consumption, high maintenance costs and increased risk of accidents and calamities.

The moment an asset will no longer be fit for use can seldom be determined at the time the asset is designed. Such a determination depends strongly on criticality, operational conditions and environmental conditions. This results in a very large spread in the useful life of assets.

If an organization records its financial and technical data correctly in an asset register, it can calculate the optimal moment of replacement, asset by asset. It can insert data of similar assets in a Weibull analysis to predict future costs.

It is not possible to use past data to judge risks. A methodology called criticality ranking is used to determine which assets can cause unacceptable failures. Once these are determined, a failure mode and effect analysis (FMEA) is used to establish which causes can lead to these failures. Countermeasures and inspection programs can then be put in place to mitigate these risks and determine when an asset should be replaced.

Using a structured approach like this can save hundreds of millions of euros while at the same time preventing many failures.

REFERENCES

1	Abernethy, R. B. (2004). *The New Weibull Handbook.* North Palm Beach (Fla): Robert B. Abernethy
2	Eurelectric. (2013). *Power distribution in Europe.* Brussels: Union of the Electricity Industry
3	ISO13306:2010. (2010). *Maintenance—Maintenance terminology.* ISO.org
4	ISO55000:2014. (2014). *ISO55000: Asset Management.* ISO.org
5	Tinga, T. (2013). *Principles of loads and failure mechanisms.* London: Springer Verlag
6	Waide, P., & Brunner, C. (sd). *Energy-efficiency policy opportunities for electric motor-driven systems.* International Energy Agency