Economics of Transformer Management

Tutorial of Cigre WG A2.20

Convener: Pierre Boss, Switzerland

“Guide on Economics of Transformer Management”

Part 1 – Introduction

Part 2 – Risk Management

Part 3 – Spécification and Pourchasse

Part 4 – Operation and maintenance

Part 5 - Repair vs. Replacement Decision Process

Part 2 – Risk Management

Daniel Bernoulli wrote in 1731:

"the *value* of an item must not be based on its *price*, but rather on the *utility* that it yields"

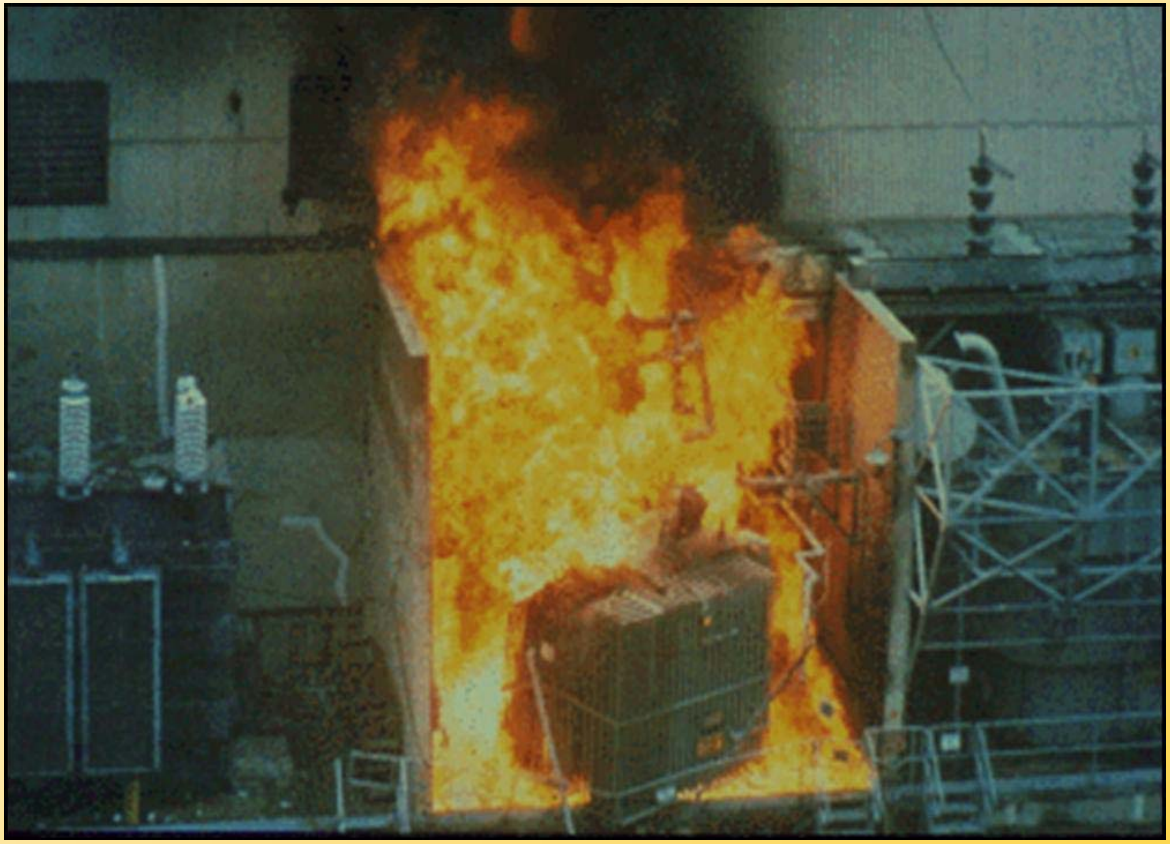
"the utility is dependent on the particular circumstances of the persons making the estimate"

"The utility resulting from a small increase in wealth will be inversely proportionate to the quantity of goods previously possessed"

Hence, he applied measurement to something that cannot be measured, blending intuition and measurement.

What is risk?

RISK IS <u>EXPECTED</u> LOSS OF UTILITY



Seconds after explosion...

Risk analysis contains three major parts

Hazard identification events (or chain of events) that should be selected for analysis

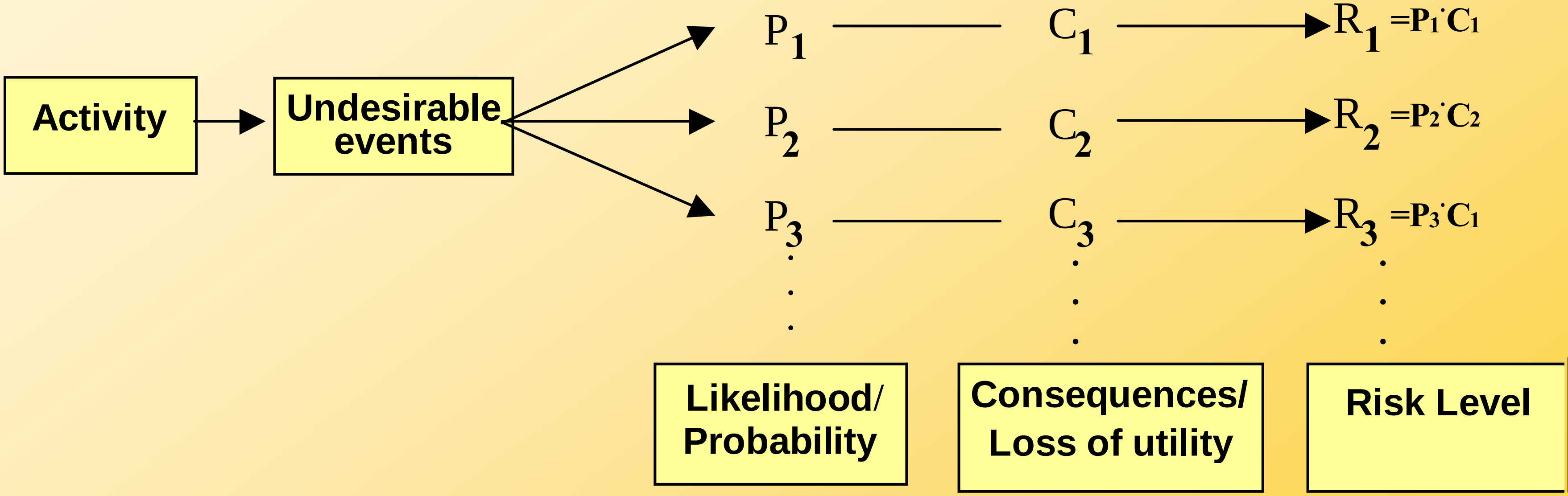
Determination of the **likelihood** of the unwanted event.

- Occurrence frequency of the event, or its probability.
- Analysis of known history, i.e. analysis of statistical data, or estimates based on judgements by experts

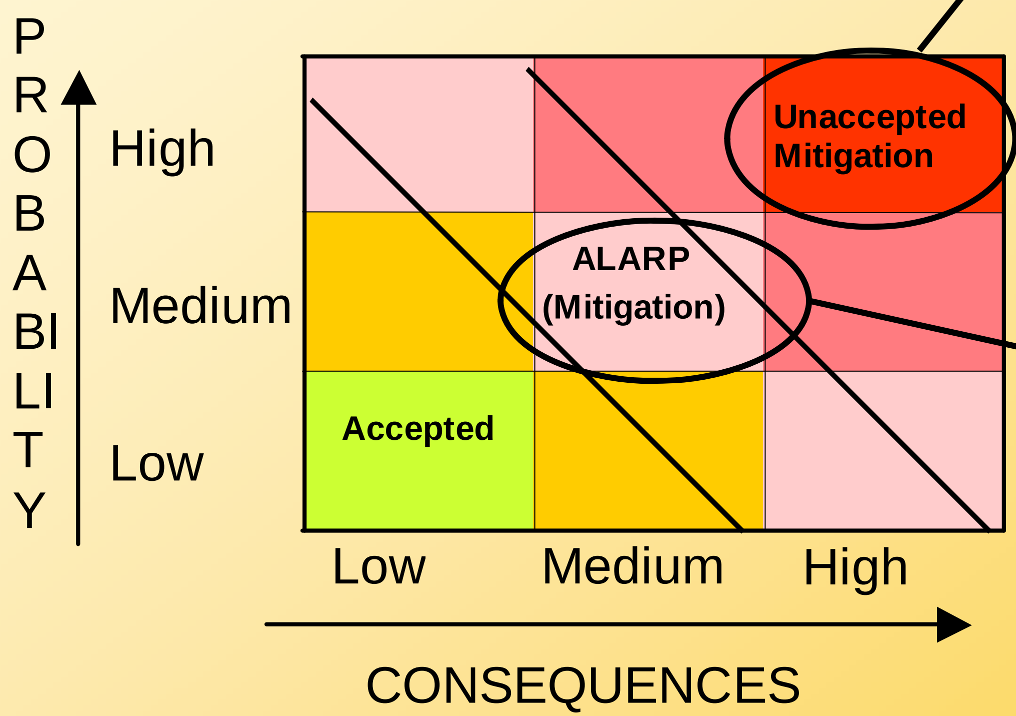
Evaluation of the **consequences** of the unwanted events

- Evaluation of risk acceptability threshold
- Tolerance level (risk aversion).

Risk Analysis Model



Risk perception and acceptability



Not acceptable/ tolerable, risk-reducing activities must be applied

Reduce the risk: As Low As Reasonably Practicable

Managing risk for a transformer population

In a deregulated energy market

- **customers demand a high reliability**
- **system owners demand higher profits**

There is a need for an asset management methods taking into account the risk involved for postponing reinvestment

In some countries legislators have introduced penalties for Energy Not Served (ENS) to promote reinvestment and insure network reliability

Managing risk for a transformer population

The need for a risk-based attitude to justify, and prioritise, reinvestments have been identified

Two methods are proposed:

- **The increased lifetime method**
- **The ranking method**

The increased lifetime method

- If a utility decides to increase the service period of one or several components in the grid, the utility must also expect that future failure rates for these components will increase.
- This means increased future costs for
  - maintenance
  - repair
  - ENS
- The decision criteria is minimisation of overall costs related to reinvestment, maintenance, repair and ENS

The increased lifetime method

Reinvestment costs saving $\Delta Cost_{reinvestment}$ is derived from interest rate and depreciation of new equipment

Increase in maintenance cost $\Delta Cost_{maintenance}$ is derived from increased in maintenance, repair and ENS costs for older units

It is considered that the current failure rate $\lambda_{component}$ will increase with time until it reach a value $\lambda_{balance}$ such that

$$\Delta Cost_{reinvestment} = \Delta Cost_{maintenance}$$

$$= \#_{component} * \lambda_{balance} * \Delta Cost_{average}$$

The increased lifetime method

Risk analysis will identify components groups which satisfy the following two criteria:

- Life extension of this component results in major reinvestment cost savings
- A significant increase in the existing failure rate is needed before the reinvestment cost savings are balanced by the increased costs for maintenance and repair, and compensating ENS

The increased lifetime method

Annual saving is larger in the early years of replacement deferral and then the rate decreases as time passes and failure rate increases

As the failure rate increases in the analysis period, the annual reinvestment cost savings will be reduced and may become negative

Monitoring the development of the annual failure rate allow the utility to revaluate the cost-benefit of the postponement of reinvestments

The Ranking Method

The relevance of preventive or corrective action on a set transformers can be based on considering two factors:

GSI (Global Strategic Impact) is a number expressing <u>the impact on the system</u> of a possible failure of a given transformer

GTC (General Technical Condition) is a number expressing the <u>probability of failure</u> of a given transformer

The Ranking Method

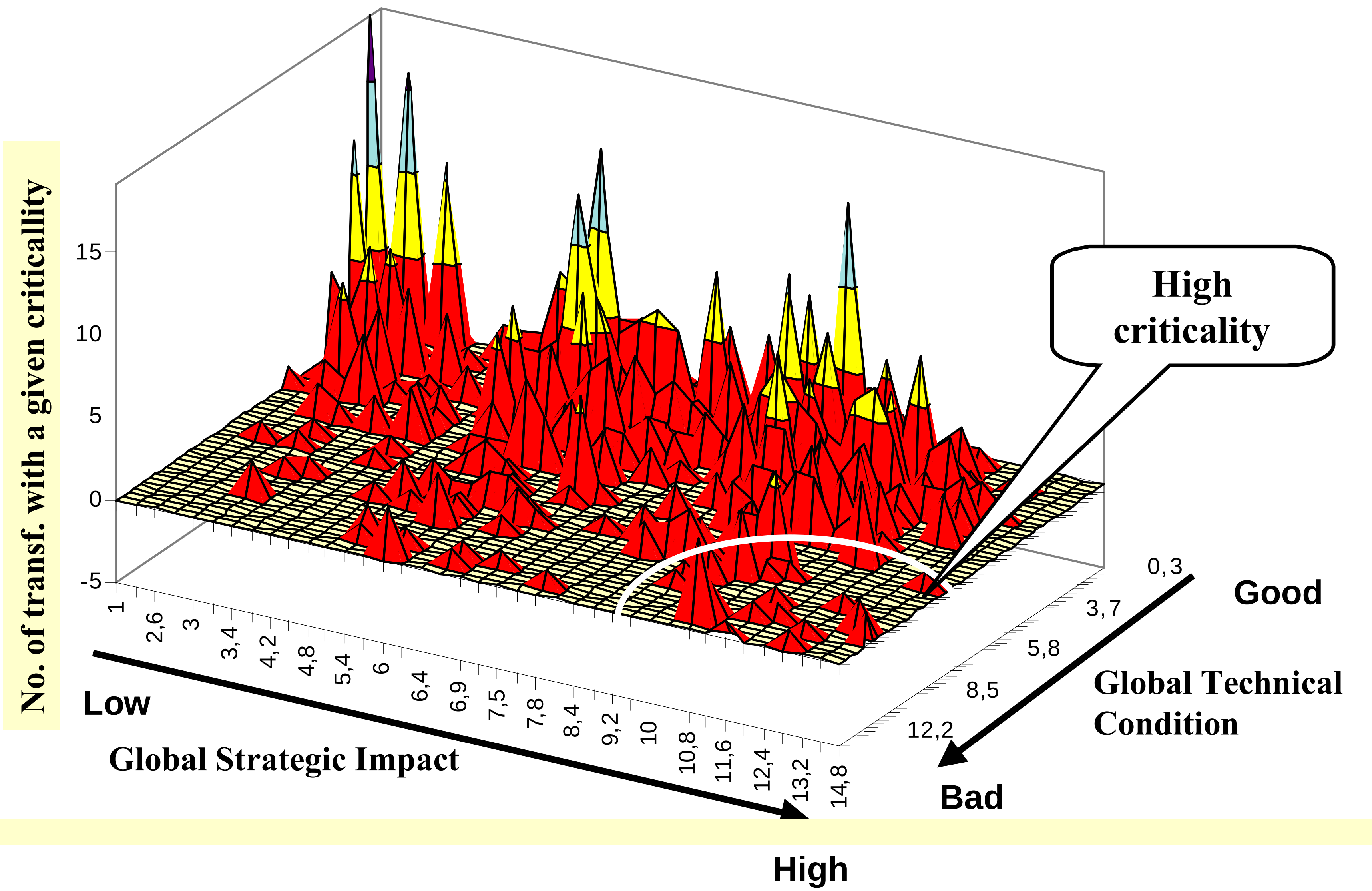
GSI (Global Strategic Impact)

- **Safety of property and persons**
- **Safety of the electrical system**
- **Environment**
- **Competitiveness**
- **Company image**
- **…**

The Ranking Method

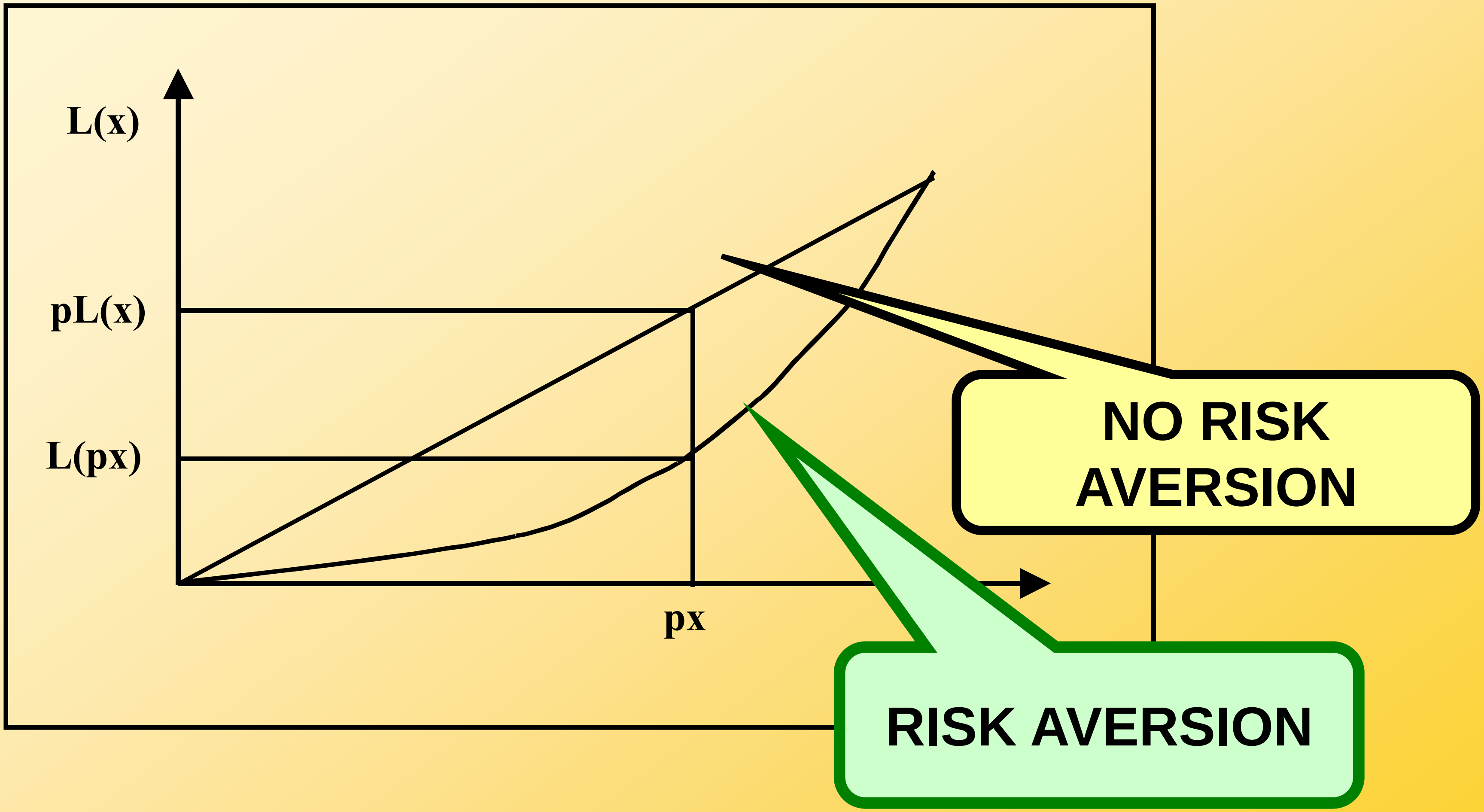
GTC (General Technical Condition)

- **The transformers State of Health**
- **Technological risk**
- **The weight of the past**
- **Operating Conditions**
- **…**



Example of GSI and GTC mapping for a population of 900 transformers.

Risk aversion profile – loss function



Bayesian decision method

$$P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$$

The Bayesian formula uses new information to revise probabilities based on the old information, or in other words to calculate future probability distributions based on previous occurrences and new information, e.g. expert opinions.

Bayes contribution was remarkably modern:
There is no single answer under condition of uncertainty.

BAYESIAN DECISION METHOD – FAULTED TRANSFORMER BAD INSULATION PAPER – INSPECT/REPAIR OR WAIT?

S = { The transformer is in a **S**eriously bad condition }

L = { The transformer is in a **L**ittle/slightly bad condition }

N = { The transformer is in a **N**ormal/good condition }

+ = {The test gives a positive result }

- = { The test gives a negative result }

2% of ”all” transformers have seriously bad paper.

10% are somewhat better, but still slightly bad.

88% of ”all” transformers have good paper.

Bayesian decision method – faulted transformer

a) Taking one sample, the test in 90% of the cases gives a positive result when taken from a transformer in a seriously bad condition (i.e. 10% false negative).

b) Correspondingly gives the test a positive result in 60% of the cases when applied on a transformer in a slightly bad condition, and

c) Finally the test gives a completely wrong answer in 10% of the cases when administered on a healthy - normal transformer (i.e. 10% false positive).

Bayesian decision method – faulted transformer

We want to find *P*(*S*|+):

$$P(S|+)=\frac{P(+|S)\cdot P(S)}{P(+|S)\cdot P(S)+P(+|L)\cdot P(L)+P(+|N)\cdot P(N)}$$

$$P(S|+)=\frac{0{,}90\cdot 0{,}02}{0{,}90\cdot 0{,}02+0{,}60\cdot 0{,}10+0{,}10\cdot 0{,}88}=0{,}11$$

This is problematical low if this result is to be the foundation for a multimillion Euro reinvestment….

Bayesian decision method – faulted transformer

Lets take another paper sample and send to Maja in Ljubljana for a DP analysis.

We introduce:

+1 = { First test is positive. }

+2 = { Second test is positive. }

Hence, we hunt: $P(S \mid +1 \cap +2)$

This is the probability for the transformer, really being in a seriously bad shape, given both test results are positive.

Bayesian decision method – faulted transformer

In stead of using the starting point $P(S)$, $P(L)$ and $P(N)$, based on our general transformer statistics, we now take the starting point with the *updated* probabilities $P(S|+1)$, $P(L|+1)$ and $P(N|+1)$ based on the information, the known fact, the result of the first test was positive:

$$P(S|+1) = P(S|+) = 0{,}11$$

$$P(L\,|+1) = \frac{0{,}60 \cdot 0{,}10}{0{,}90 \cdot 0{,}02 + 0{,}60 \cdot 0{,}10 + 0{,}10 \cdot 0{,}88} = 0{,}36$$

$$P(N\,|+1) = \frac{0{,}10 \cdot 0{,}88}{0{,}90 \cdot 0{,}02 + 0{,}60 \cdot 0{,}10 + 0{,}10 \cdot 0{,}88} = 0{,}53$$

Bayesian decision method – independence of the tests

If we want to calculate the probability for the second test result being positive, given the transformer is in a serious bad shape, this second test is not dependent on the result of the first test. We have:

$$P(+2 \mid S \cap +1) = P(+2 \mid S) = P(+ \mid S) = 0{,}90$$

$$P(+2 \mid L \cap +1) = P(+2 \mid L) = P(+ \mid L) = 0{,}60$$

$$P(+2 \mid N \cap +1) = P(+2 \mid N) = P(+ \mid N) = 0{,}10$$

Bayesian decision method –probabilities second test

We replace *P(S)*, *P(L)* and *P(N)* with *P(S|+1)*, *P(L|+1)* and *P(N|+1)*, and by again using Bayes formula:

$$P(S\,|+1\bigcap+2)=\frac{0{,}90\cdot 0{,}11}{0{,}90\cdot 0{,}11+0{,}60\cdot 0{,}36+0{,}10\cdot 0{,}53}=0{,}27$$

$$P(L\,|+1\bigcap+2)=\frac{0{,}60\cdot 0{,}36}{0{,}90\cdot 0{,}11+0{,}60\cdot 0{,}36+0{,}10\cdot 0{,}53}=0{,}59$$

$$P(N\,|+1\bigcap+2)=\frac{0{,}10\cdot 0{,}53}{0{,}90\cdot 0{,}11+0{,}60\cdot 0{,}36+0{,}10\cdot 0{,}53}=0{,}14$$

Bayesian decision method – two decisions

D1 = { The transformer is moved immediately to the factory for inspection and possibly repair. }

D2 = { Wait some time and see. }

Our power engineer assess the transformer and tabulate the loss of utility:

		Transformer condition:		
		S	L	N
Decision:	D1	0	50.000	50.000
	D2	200.000	25.000	0

Bayesian decision method – transformer seriously bad

We see from the table the loss of utility is 0 if the transformer is in a seriously bad condition and the engineer rightly advises management to "hospitalise" the transformer at once (S-D1).

If the engineer advises wrongly to wait and see (D2) in this situation, the most serious fault is done when the transformer fails with a loss of utility being a 200.000, due to cost of Energy Not Served and the extra cost for unplanned moving and repair (S-D2).

		Transformer condition:		
		S	L	N
Decision:	D1	0	50.000	50.000
	D2	200.000	25.000	0

Bayesian decision method – transformer a little bad

If the transformer is in a slightly bad condition, the loss of utility is the cost for transportation and inspection, 50.000, which is the same in both cases (D1-L) and (D1-N).

If it is necessary to dry and reclamp the windings in case (D1-L), the cost for doing this is of course not a loss of utility, and may even lead to a reduction in the loss of utility due to the increased life time expectancy, and the reduced failure rate, of the refurbished transformer.

		Transformer condition:		
		S	L	N
Decision:	D1	0	50.000	50.000
	D2	200.000	25.000	0

Bayesian decision method – transformer normal

If the transformer is in a good condition and the engineer advises to wait and see (D2-N), again the loss of utility is 0.

If, in this good condition, the transformer is moved to the factory, the second worst decision is taken (D1-N) with a loss of utility of 50.000. The loss of utility may even be higher as the moved, inspected and not repaired transformer may be faulted during transportation and handling, and thus may have a higher probability for a future failure than before moving.

		Transformer condition:		
		S	L	N
Decision:	D1	0	50.000	50.000
	D2	200.000	25.000	0

Bayesian decision method – expected loss of utility

This means it is necessary to weigh together the loss of utility for the different thinkable conditions that may arise, where the weights are the best estimated probabilities for these conditions.

Hence, the appurtenant risk with the decision to "hospitalise" the transformer at once, RD1, is:

$$RD1 = 0 \cdot P(S \mid +1 \bigcap +2) + 50.000 \cdot P(L \mid +1 \bigcap +2) + 50.000 \cdot P(N \mid +1 \bigcap +2) =$$
$$= 0 \cdot 0{,}27 + 50.000 \cdot 0{,}59 + 50.000 \cdot 0{,}14 = 36.500$$

		Transformer condition:		
		S	L	N
Decision:	D1	0	50.000	50.000
	D2	200.000	25.000	0

Bayesian decision method – expected loss of utility

Corresponding, the appurtenant risk for "wait and see", RD2, is:

$$RD2 = 200.000 \cdot 0{,}27 + 25.000 \cdot 0{,}59 + 0 \cdot 0{,}14 = 68.750$$

		Transformer condition:		
		S	**L**	**N**
Decision:	**D1**	**0**	**50.000**	**50.000**
	D2	**200.000**	**25.000**	**0**

Bayesian decision method – expected loss of utility

The risk for "hospitalise" at once, RD1: 36.500
The risk for "wait and see", RD2: 68.750

Consequently we see the expected loss or risk for a "wait and see" decision is (here!) much higher than the risk for "hospitalising" the transformer at once.

If this was the only available information, the engineer should advise the management to decide upon the first decision (RD1), regardless the best estimated probability for the transformer being in a seriously bad condition is as low as 0,27.

A brief sensitivity analysis shows this decision to be robust for relatively gross changes in the costs chosen.

Spare Transformers

Risk mitigation by use of spare transformers

- **to optimize the quantity**
- **to minimize costs**
- **associated with purchasing, storing, handling and maintaining**

A consistent and documented cost/risk analysis process should be adopted

Spare Transformers

Factors that must be evaluated and appraised:

- **the costs of purchase, store and maintain spares**
- **consequences of not having a spare in event of a failure**
  - **size of the population**
  - **failure rate**
  - **lead time to replace or repair**
  - **probability for N-2 situations**

Spare Transformers

Example of calculation:

- **Group of 47 transformers**
- **In most cases 2 transformer per substation**
- **Failure rate (for costly failures) : 0.4% per year**
- **Practically no option for load transfer**
- **Repair time : 9 months**
- **Loss of two transformers entail loss of 100MVA load**
- **Value to the community of lost load = $10 000/MWhr**

Spare Transformers

For the 47 tanks the probability of a transformer failure in one year (p.a.):

- **major failure = 0.004 x 47 = 0.188**
- **minor failure rate = 0.03**

Spare Transformers

Probability of loss of station (N-2) during transformer repair time of 9 months (0.75 year):

- **Reserve transformer fault: 0.03 x 0.75 = 0.023**
- **Circuit breaker faults: 0.03 x 0.75 x 2 = 0.046**
- **Isolator fault: 0.03 x 0.75 x 2 = 0.046**
- **CT, bus, SA fault: 0.046 = 0.046**
- **Weather, animals: 0.03 x 0.75 = <u>0.023</u>**
- **Total probability of a minor failure = 0.18**

Spare Transformers

Probability of both events (N-2): 0.188 x 0.18 = 0.03384

Cost of second transformer failure (N-2):

Average power not supplied: = 100 MW

Energy not supplied per day: 100 x 24 hrs = 2,400 MWh

Based on minor outage duration of 2 days:

Total energy lost : 100 MW x 48h = 4,800 MWh

The cost of an outage: 10,000$ x 4,800 = 48 M$

Spare Transformers

The cost of risk in each year: 0.03384 x $48m = $1.62 M$

An economic analysis shows:

Present value cost of a spare = $2.6 M$

Present value cost of failure risk = $16.7 M$

This is a strong case to purchase one spare transformer

Part 3 - Specification and Purchase

Specific needs may have a significant impact on cost:

	Cost increase
•Tertiary delta stabilizing winding	7% - 8%.
•On-load tap changers (+/- 10%)	15 – 20%
extra for +/- 20%	5%
•De-energised tap changer	8 – 12%

Specification and Purchase

An increased overloading capability can have an impact on the weight and the costs

$$\frac{m_2}{m_1} = \left(\frac{S_2}{S_1}\right)^{3/4} \qquad \frac{Cost_2}{Cost_1} = \left(\frac{S_2}{S_1}\right)^{0,5-0.6}$$

- **m : mass,**
- **S : rated power,**
- **indexes “1” and “2” stand for transformer 1 and 2**

Specification and Purchase

- **Fire resistant oil or biodegradable oil might be justified in some applications although it raise significantly the cost**
- **Sound level regulation can force a lower induction level in the core**
- **Capitalisation of losses might increase the cost of the transformer if induction level in the core and current density in winding need to be reduced**

Part 4 -Operation and Maintenance

- **Generation and supply of electricity is now more in line with normal business model with financial performance starting to have as much bearing on decision making as engineering requirements used to have.**
- **More stringent contractual arrangements with their customers and failure to deliver power can impose severe financial penalties**
- **Shareholder pressure for financial performance often will reduce the resources available to the transformer manager**
- **Insurance companies which will operate in many countries and continents may seek changes in practices in a utility in order to bring them closer to other utilities which they insure**

Part 4 -Operation and Maintenance

How long should a transformer remain in service?

From the economic management perspective, power transformers differ from other network assets :

- **Capital cost to O&M cost ratio is very large**
- **No significant increase in failure rate with age indicated at present**
- **Failures tend to be of a random nature**
- **No generally established criterion for technical end-of-life**
- **Transformer load is generally lower than rated load**
- **Unit failure is often ‘acceptable’ ((n-1) criterion)**

How long should a transformer remain in service?

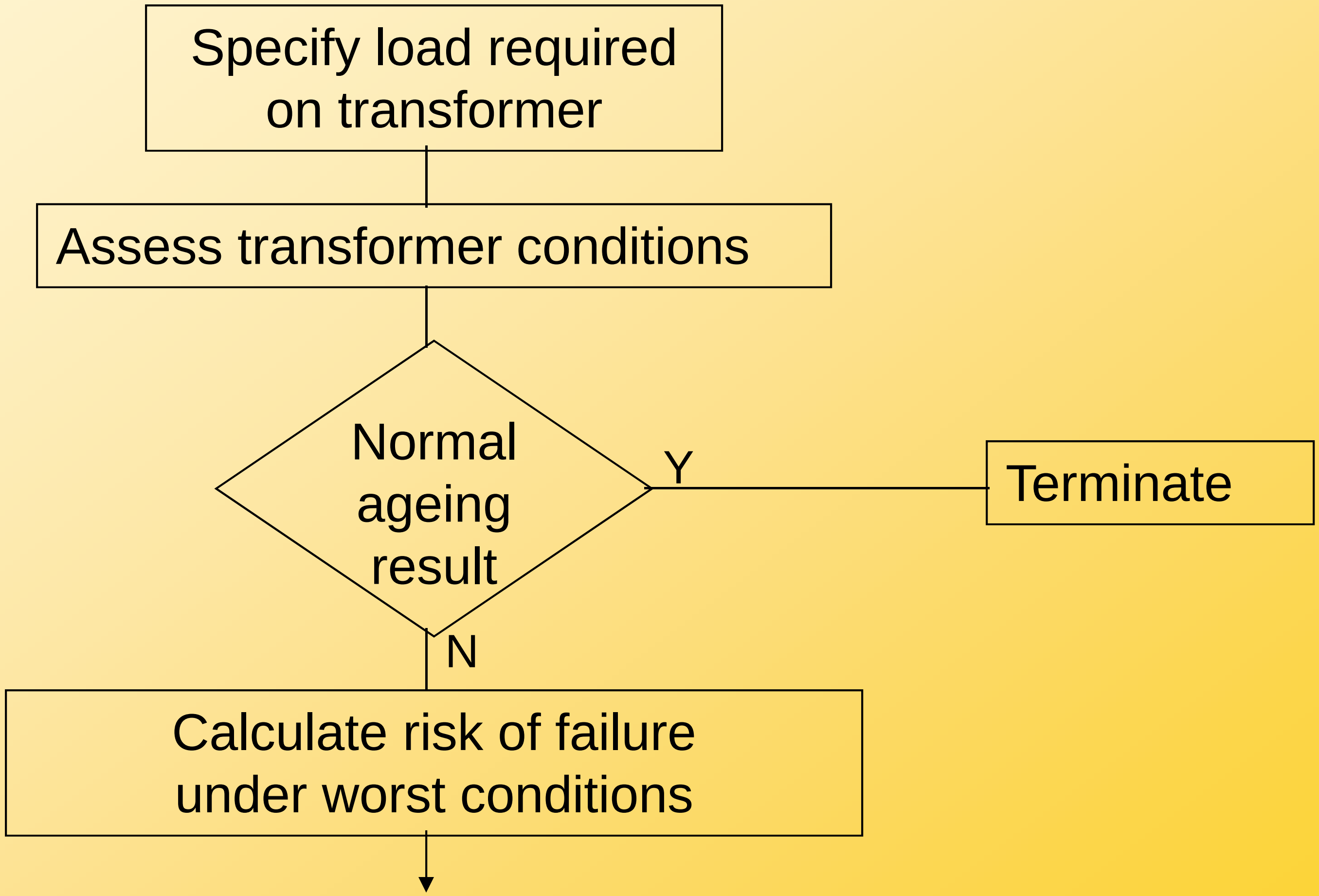
- When traditional economic tools are applied to transformer management, deferring replacement is generally the preferred option
- Factors other than economics influence the decision:
  - Environmental
  - Public relations
  - Traditional practices
  - Perceived risk reduction
- Economical model for replacement of old transformer is driven basically by risk increase

Loading limits on aged transformers

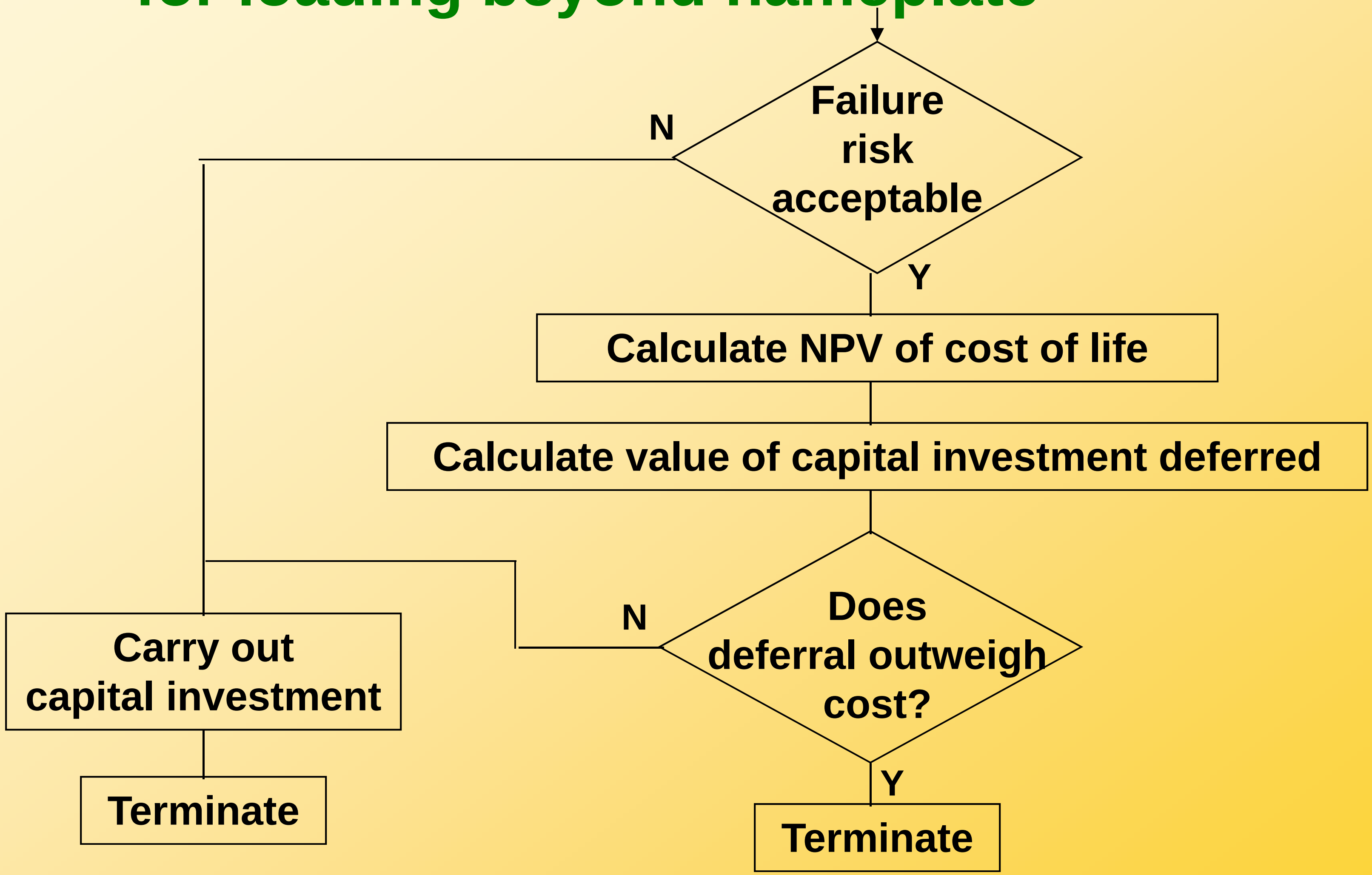
Loading policy must consider various factors:

- **Transformer specifications**
- **Transformer condition including age**
- **Environmental conditions**
- **Electrical operating conditions**
- **Type of loading**
- **Acceptable loss-of-life**
- **Risk of major/minor failure including financial loss**
- **Insurance impact**
- **Financial benefits of loading policy .**

Decision making model for loading beyond nameplate



Decision making model for loading beyond nameplate



Assessing the cost of an outage

The following issues need to be considered

- **Efficient generation dispatch**
- **Efficient network loading**
- **Length of outage period**
- **Weather conditions (seasonal)**
- **Transformer condition**
- **Emergency return-to-service time allowed**
- **Maintenance work optimization**
- **Spare part availability.**

Assessing the cost of change in operating conditions

Network evolution often led to significant changes in voltage regulation regime.

Various factors need to be considered:

- **Tapping range suitability**
- **Number of OLTC operations per year**
- **BIL level (including bushings)**
- **Lightening protection**

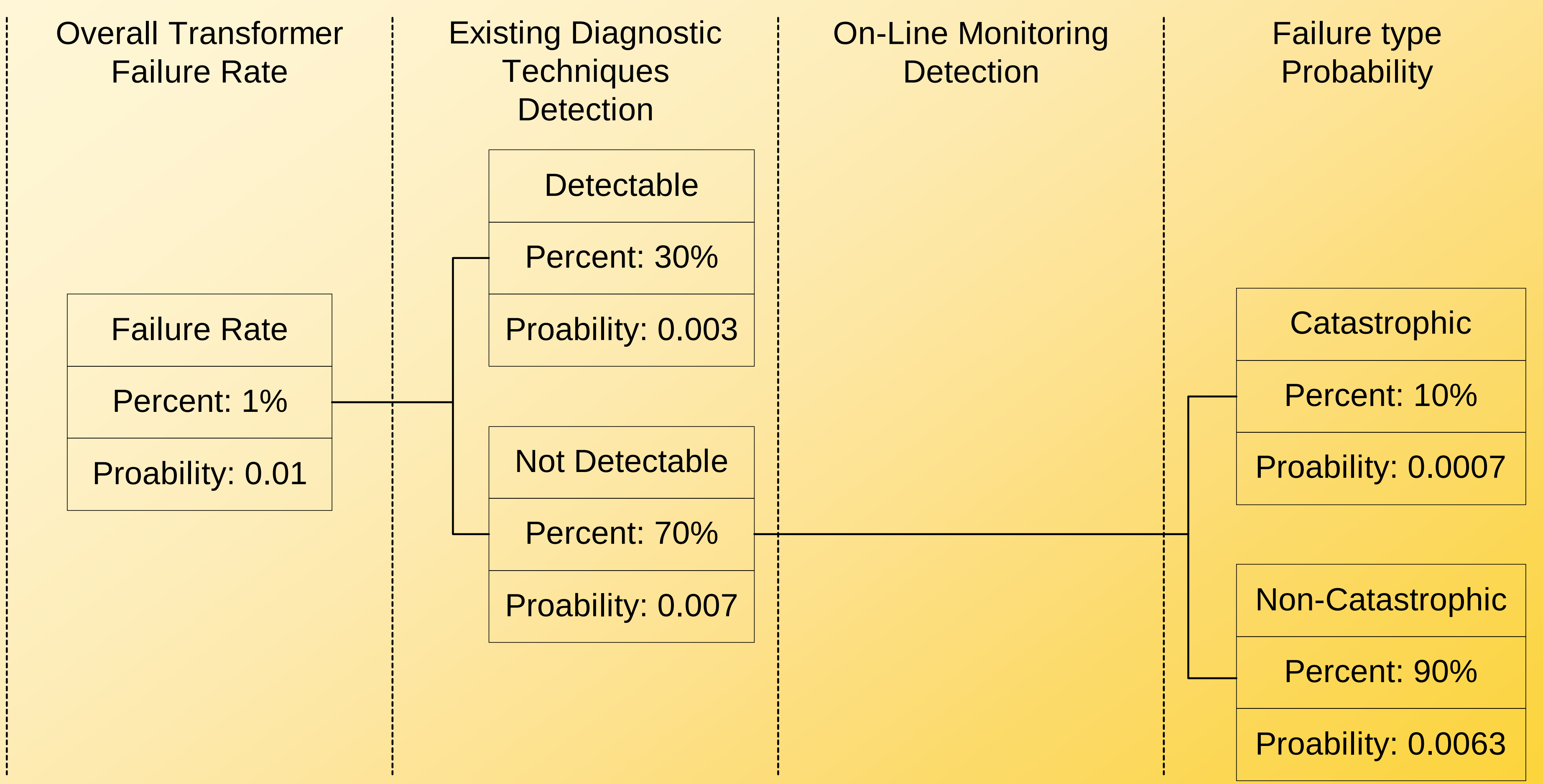
Optimizing maintenance cost

- Transformers generally are high reliability equipments with a low maintenance cost
- Rarely, maintenance costs result in a decision to replace a transformer but it will often result in the decision to replace transformer accessories such as fans, OLTC drive mechanisms etc.
- Regular maintenance activities include:
  - replacing breather consumables,
  - checking oil levels,
  - DGA tests,
  - cleaning bushings,
  - checking for leaks, corrosion repairs,
  - functional tests on OLTC and fans\pumps,
  - protection systems tests etc.

Optimizing of cost for On-Line monitoring

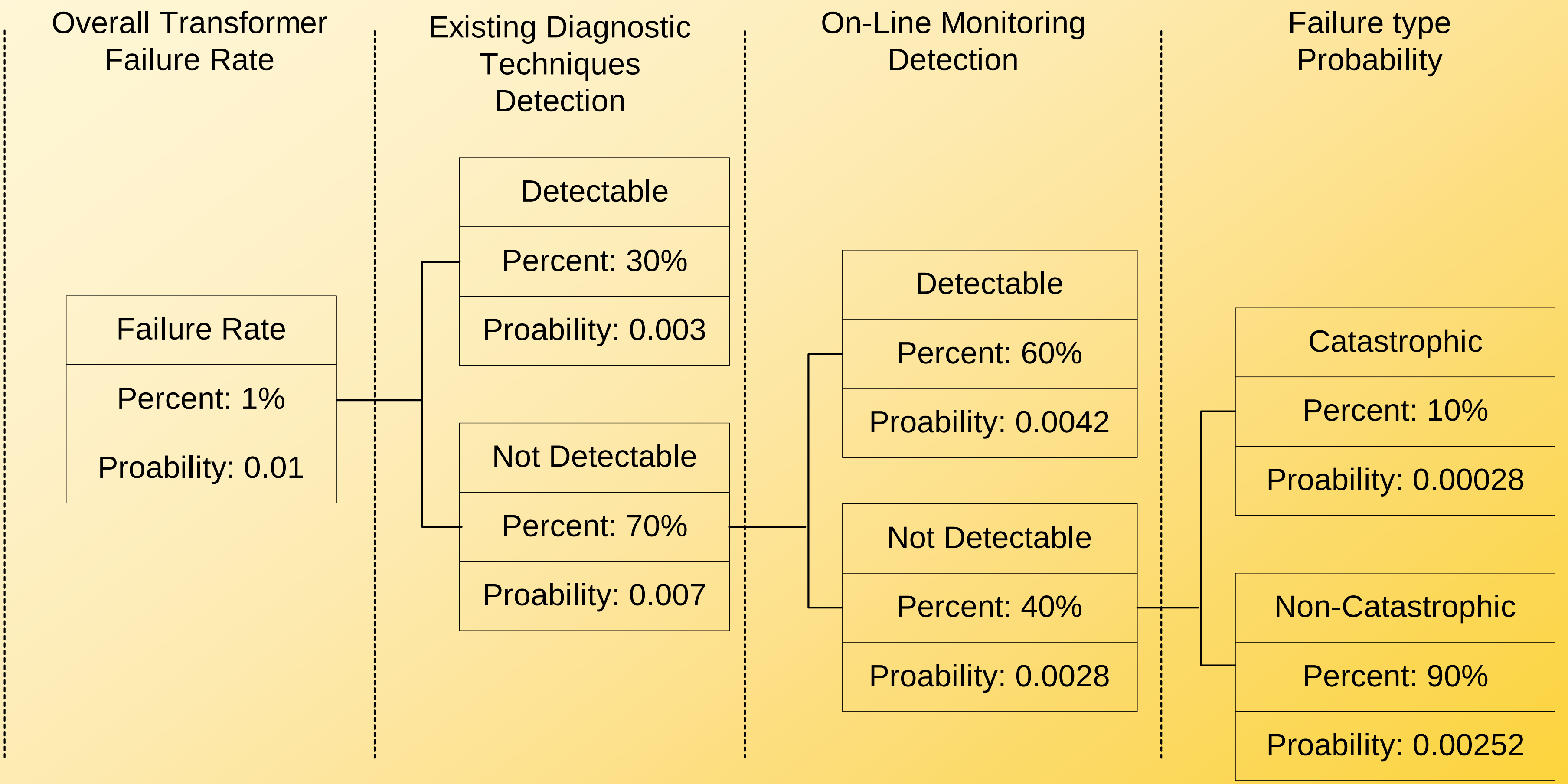
- **Today, many transformer parameters can be cost effectively monitored continuously**
- **Assessment of monitoring value imply:**
- **Cost:**
  - **Cost of equipment and training**
  - **Equipment reliability and maintenance costs**
  - **Cost of data archiving and retrieval**
- **Benefits:**
  - **Value of information**
  - **Benefit of increased reliability or earlier detection of impending failure**
  - **Future benefit of additional information for transformer condition determination**
  - **Reduction of insurance costs**

Effect of monitoring on failure rate



Failure probability tree without monitoring

Effect of monitoring on failure rate



Failure probability tree with monitoring

Economic benefit of monitoring

Values needed for assessment of economic benefit

- **Repair cost of major failure € 1,500,000**
- **Catastrophic failure multiple (300%) € 4,500,000**
- **Early repair to major repair ratio (20%) € 300,000**
- **On-line Monitoring System (assume 20 year life span):**
  - **System Cost € 40,000**
  - **Installation € 5,000**
  - **Maintenance Cost (annual) € 1,000**

Economic benefit of monitoring

Annual Repair Cost Without On-Line Monitoring (for faults currently undetected)

Major Failure	(€1,500,000 * 0.0063) =	€ 9,450
Catastrophic Failure	(€4,500,000 * 0.0007) =	€ 3,150
Annualized Cost		***€12,600***

Annual Repair Cost With On-Line Monitoring

Major Failure	(€1,500,000 * 0.00252) =	€ 3,780
Catastrophic Failure	(€4,500,000 * 0.00028) =	€ 1,260
Early Detection Repair	(€300,000 * 0.0042) =	€ 1,260
Monitoring System Cost	(€45,000 / 20) =	€ 2,250
Monitoring System Maintenance:		€ 1,000
Annualized Cost		***€ 9,550***

Annual Benefit of On-Line Monitoring **€ 3,050**

Economic benefit of monitoring

Additional cost for energy not sold (GSU transformers)

$$\begin{pmatrix} Annual\,Cost \\ for\,Energy \\ not\,Generated \end{pmatrix} = \begin{pmatrix} Lost \\ Power \\ (MW) \end{pmatrix} \times \begin{pmatrix} Outage \\ Duration \\ (Hours) \end{pmatrix} \times \begin{pmatrix} Cost\,of \\ \mathrm{Re}placement\,Energy \\ (\$/MWh) \end{pmatrix} \times \begin{pmatrix} Major \\ Failure \\ Rate \end{pmatrix}$$

Economic benefit of monitoring

Degraded System Operation

- Major outage probability without monitoring 0.007
- Major outage probability with monitoring 0.0028
- Major outage duration 0.2 Years
- Minor outage probability 0.05

2^{nd} Contingency probability

- Without monitoring: 0.007 * 0.2 * 0.05 = 0.00007
- With monitoring: 0.0028 * 0.2 * 0.05 = 0.000028

Economic benefit of monitoring

Penalty for Energy not Delivered (VOLL)

- 2nd contingency probability without monitoring : 0.00007
- 2nd contingency probability with monitoring : 0.000028
- Minor outage duration: 16 Hours
- Lost power : 200MW
- VOLL penalty : €10 000 / MWh

Annual cost for VOLL

- Risk-cost without monitoring: (200 * 16 * 10000) * 0.00007 = € 2240
- Risk-cost with monitoring: (200 * 16 * 10000) * 0.000028 = € 896

Annual Benefit of On-Line Monitoring € 1344

Off Line Condition Assessment

- **New diagnostic tools are becoming available**
- **Fault finding activity in now being expanded toward widespread benchmarking**
- **Economic value is assess as previously describe for On-line monitoring**
- **Additional costs for outage may need to be considered**

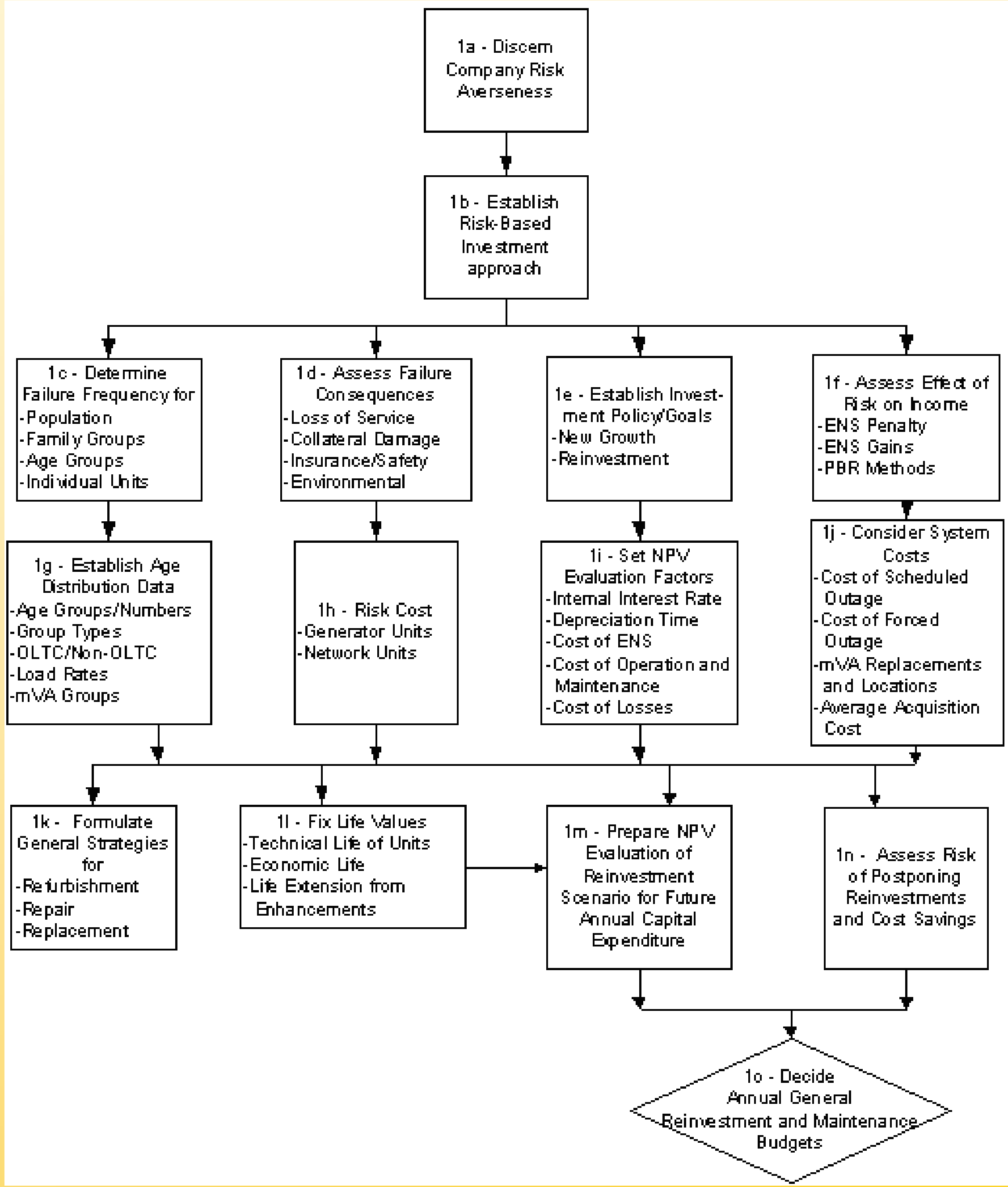
Database for Transformer Management and Condition Assessment

- **Data repository increase the value of condition assessment activity by allowing the establishment of trends and family behavior.**
- **Transformer characteristics need to be recorded in this data bank.**
- **For condition base maintenance (CBM) limit values may be defined for key conditions.**
- **Data generated by On-Line monitoring or Off-Line tests should be archived**
- **All relevant data concerning a transformer outage should also be archived (reason for outage, failure mode, failure causes, remedial action) (To be developed by WG A2-23)**

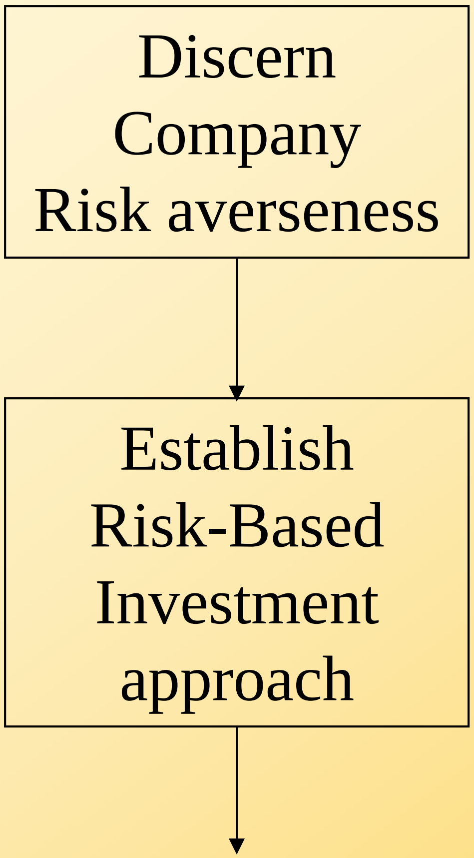
Part 5 - Repair vs. Replacement Decision Process

- **It is not practical to set a single set of rules that would suit all utilities**
- **A Normative Model is proposed, presenting a set of knowledge-based tools that prescribe a course of action leading to decisions.**
- **The flow chart is designed to guide the user through a series of activities leading to decisions necessary in taking a specific action or to arrive at a specific result.**
- **This decision process is intended for failed or trouble units**

Phase 1 Determination of Risk and Investments Policy



Determination of Risk and Investments Policy



Electric utility companies, driven by their customers' needs, usually have a low tolerance for failures and hence risk-cost is a very real cost of doing business

Utility regulators are applying Performance-Based Rates (PBRs) or Energy Not Served (ENS) penalties on income.

Large reinvestment are needed and must be distributed over time.

A strategy for refurbishment and replacement is needed

Determination of Risk and Investments Policy

Determine Failure Frequency for
- Population
- Family groups
- Age groups
- Individual Units

- **Boundaries must be set on risk averseness**
- **Boundaries must include a financial mechanism for factoring risk averseness in the reinvestment strategy**
- **This evaluation method must include the change in risk-cost over time or age of equipment to be truly meaningful**

Determination of Risk and Investments Policy

Assess Failure Consequence

- Loss of service
- Collateral Damage
- Insurance / Safety
- Environmental

Some survey have indicated following progression in failure rate( )

Transformer Age	Substation Units	Generator Units
≤ 15 years	0.5%	0.8%
16-24 years	1.0%	1.5%
25-34 years	1.5%	2.0%
35-50 years	2.0%	2.5%
> 50 years	3.0%	3.5%

0.5% excellent, 2% acceptable, >2% unacceptable

Determination of Risk and Investments Policy

Establish Investment Policy/Goals
- New Growth
- Reinvestment

Studies on age distribution versus reinvestment strategy indicate that investment in refurbishment and life extension of comparatively modern and median age units (less than 35 years) is favourable to investment in new units in the short term

Determination of Risk and Investments Policy

Assess Effect of Risk on Income
– ENS Penalty
– ENS Gains
– PBR Methods

- **Loss of income can have a serious impact on the ability of the utility to reinvest**
- **Pro-active reinvestment is encouraged to reach a higher level of reliability**
- **Function of the Risk vs. Reward evaluation and the utility company's level of risk aversion**

Determination of Risk and Investments Policy

Establish Age Distribution Data
- – Age Group/Numbers
- – Group Types
- – OLTC/Non-OLTC
- – Load Rates
- – MVA Groups

- **Modern databases for collecting, sorting, and querying information can help considerably**
- **A proposed "Transformer Population Information" listing is given in ANSI/IEEE 057.117 which considers virtually all aspects of the required data to be collected**

Determination of Risk and Investments Policy

Risk Cost
- Generator Units
- Network Units

Set NPV
- Depreciation Time
- Cost of Operation and Maintenance

- **Risk-costs will differ for small and large units**
  - **failure frequency**
  - **consequential cost**

- **Net Present Value calculations require**
  - **interest rate**
  - **internal rate of return**
  - **expected lifetime**
  - **capitalized cost of losses**

Determination of Risk and Investments Policy

Formulate General Strategies for
- Refurbishment
- Repair
- Replacement

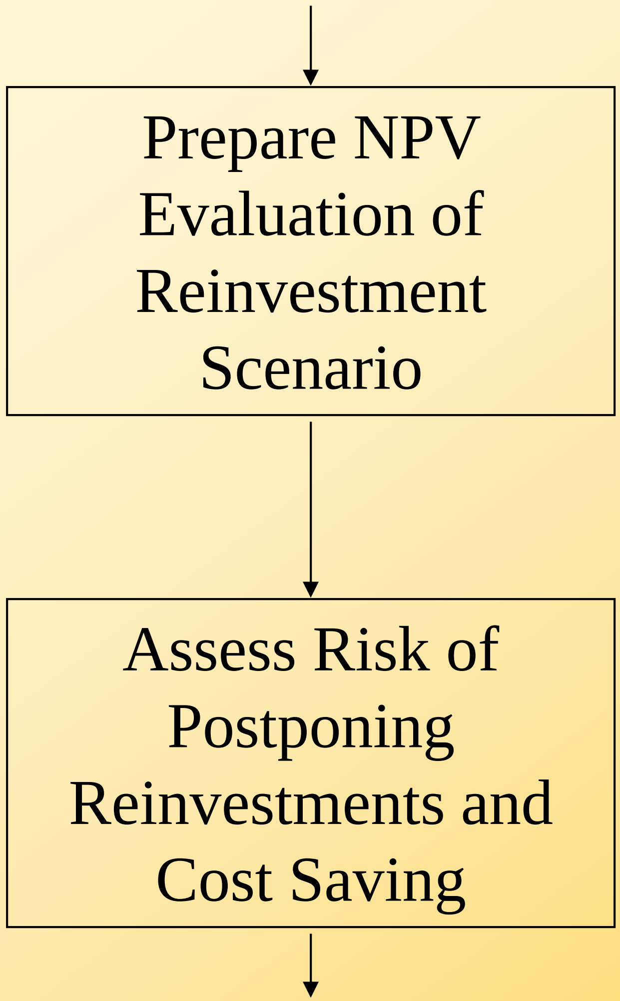
Fix Life Value
- Technical Life of Unit
- Economic Life
- Life Extension from Enhancement

- **Collect information**
  - **age distribution data**
  - **transformer groupings**
  - **available resources**
  - **logistics or unusual cost factors**

- **Set the expected limits for technical and economic life of new units and rewound / rebuild units**

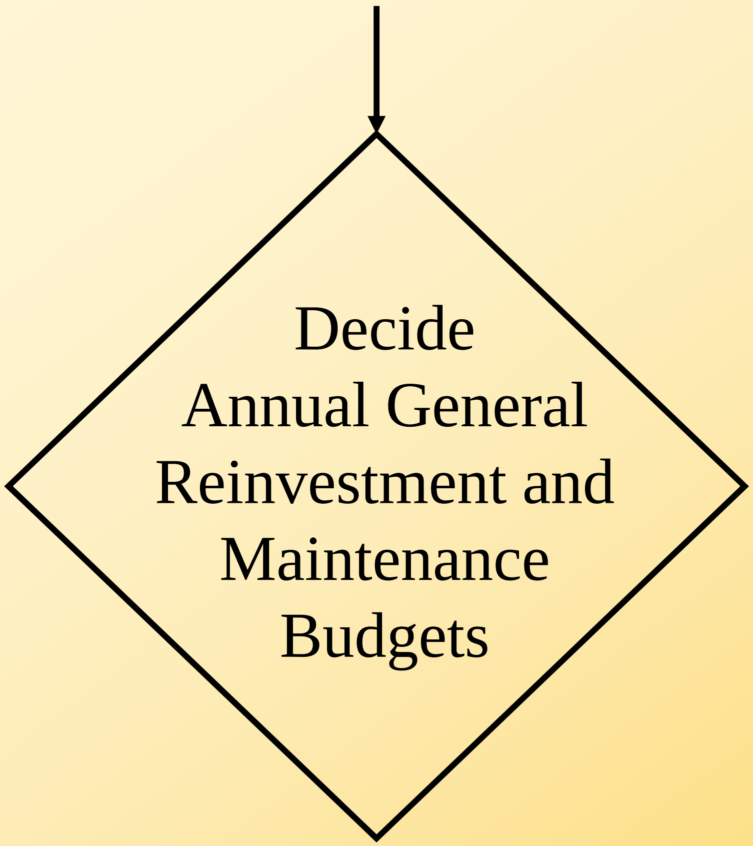
- **Consider the equivalent annual costs for each alternative**

Determination of Risk and Investments Policy



- **The risk-based NPV evaluation for the population is based on age distribution**
- **With values set for time and cost, a number of potential scenarios can be calculated to consider the distribution of future capital investment options**
- **With the predetermined risk-cost it is possible to evaluate the sensitivity of cost savings associated with reinvestment deferral**

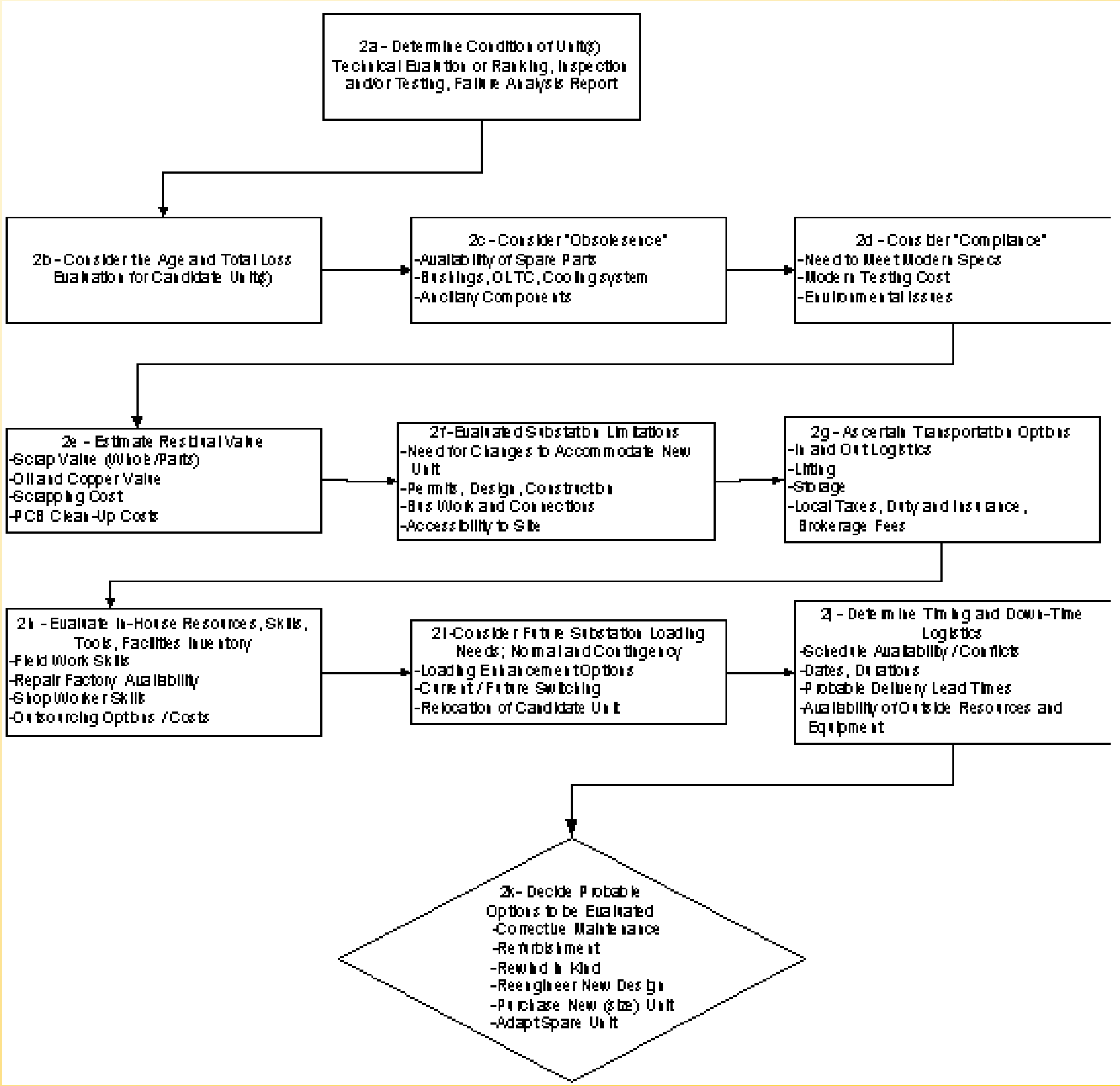
Determination of Risk and Investments Policy



- **Future reinvestment distribution is based on refurbishment and replacement strategies models**
- **Provides the ability to manage a situation that may otherwise be overwhelming**
- **Economic Modelling expressed in financial terms will considerably strengthen the Asset Manager's internal decision to select a path forward for overall reinvestment**

Phase 2

Unit Specific Investment Methodology



Unit Specific Investment Methodology

Determine
Condition of Unit(s)

- Technical Evaluation or Ranking
- Inspection and/or Testing
- Failure Analysis Report

Four different circumstances may require the asset's condition to be determined:

- **Ranking exercise as part of a life assessment**
- **Following a warning or a diagnostic test raising concern**
- **Fault indication requiring removal from service**
- **Failed unit condition. Need to determine extent of refurbishment or repair**

Unit Specific Investment Methodology

Consider the Age and Evaluate Total Loss of Candidate Unit(s)

Consider Obsolescence and availability of spare parts

- Bushings
- OLTC
- Cooling System
- Ancillary Components

- **The cost of no-load and load losses are vital in making the repair / replacement decision**
- **Unit more than 35 to 40 years old, the cost of no-load losses is often too high to consider keeping the unit**
- **A key factor is availability or obsolescence of spares parts**
- **replacement of parts by non-original requires extra money and time**

Unit Specific Investment Methodology

Consider "Compliance"

- Need to Meet Modern Specs
- Modern Testing Cost
- Environmental Issues

Estimate Residual Value

- Scrap Value
- Oil and Copper Value
- Scrapping cost
- PCB Clean-up cost

- **Opportunity presented by a failed unit to update it to modern standards during the repair process**
  - **Short-circuit withstand capability**
  - **Overload limits**
  - **Noise levels**

- **Remnants of a failed unit can have both positive and negative implications on the repair / replace decision**

- **It may have a scrap value, or it may be costly to dispose of the contaminated parts**

Unit Specific Investment Methodology

Evaluate Substation Limitations

- Need for changes to accommodate new unit
- Permits, Design, Construction
- Accessibility to site

Ascertain Transportation Options

- In and Out logistics
- Lifting
- Storage
- Local Taxes
- Duty, Brokerage,etc

- **Physical limitations of older substations can have a major impact on the decision**
- **Location of the substation may make the removal of the unit an impractical**
- **Transportation costs can be very high in some locations around the world**

Unit Specific Investment Methodology

Evaluate In-House Resources
- Field Work Skills
- Repair Factory Availability
- Shop Worker Skills
- Outsourcing Options

Consider Future Substation Loading
- Loading Enhancement
- Relocation of Unit

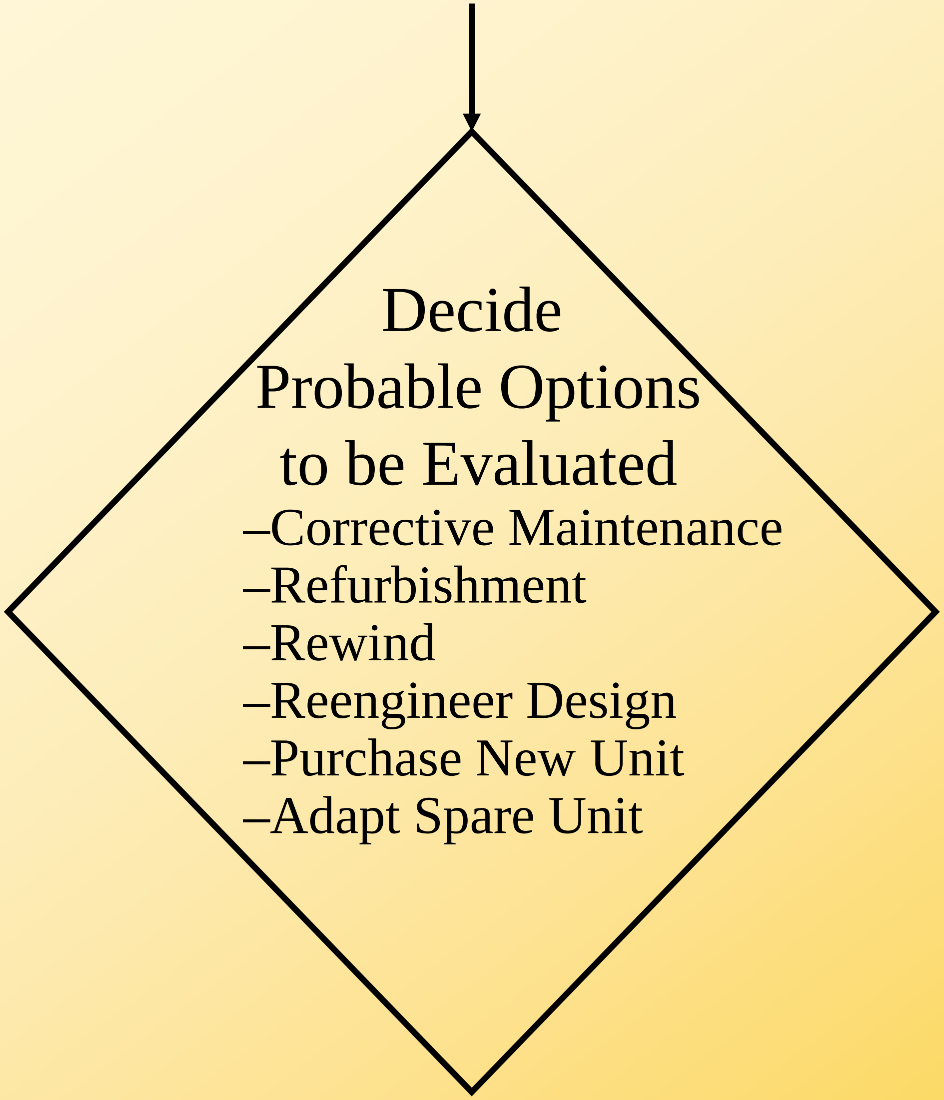
- **The practicality and economic viability of on-site refurbishment often revolves around the availability of skilled people to do the work**
- **Cost of hiring field workers and equipment is prohibitive in some locations**
- **Failed transformers are often replaced by new larger units**

Unit Specific Investment Methodology

Determine Timing and Down-Time Logistics
- Schedule conflicts
- Dates, Durations
- Probable Delivery Lead Times
- Availability of Outside Resources and Equipment

- **Cost of downtime and the potential need to reduce electrical service can have enormous financial implications**
- **The timing of a failure may not coincide with the availability of a work crew to do major refurbishment, making the purchase of a new unit a necessity**

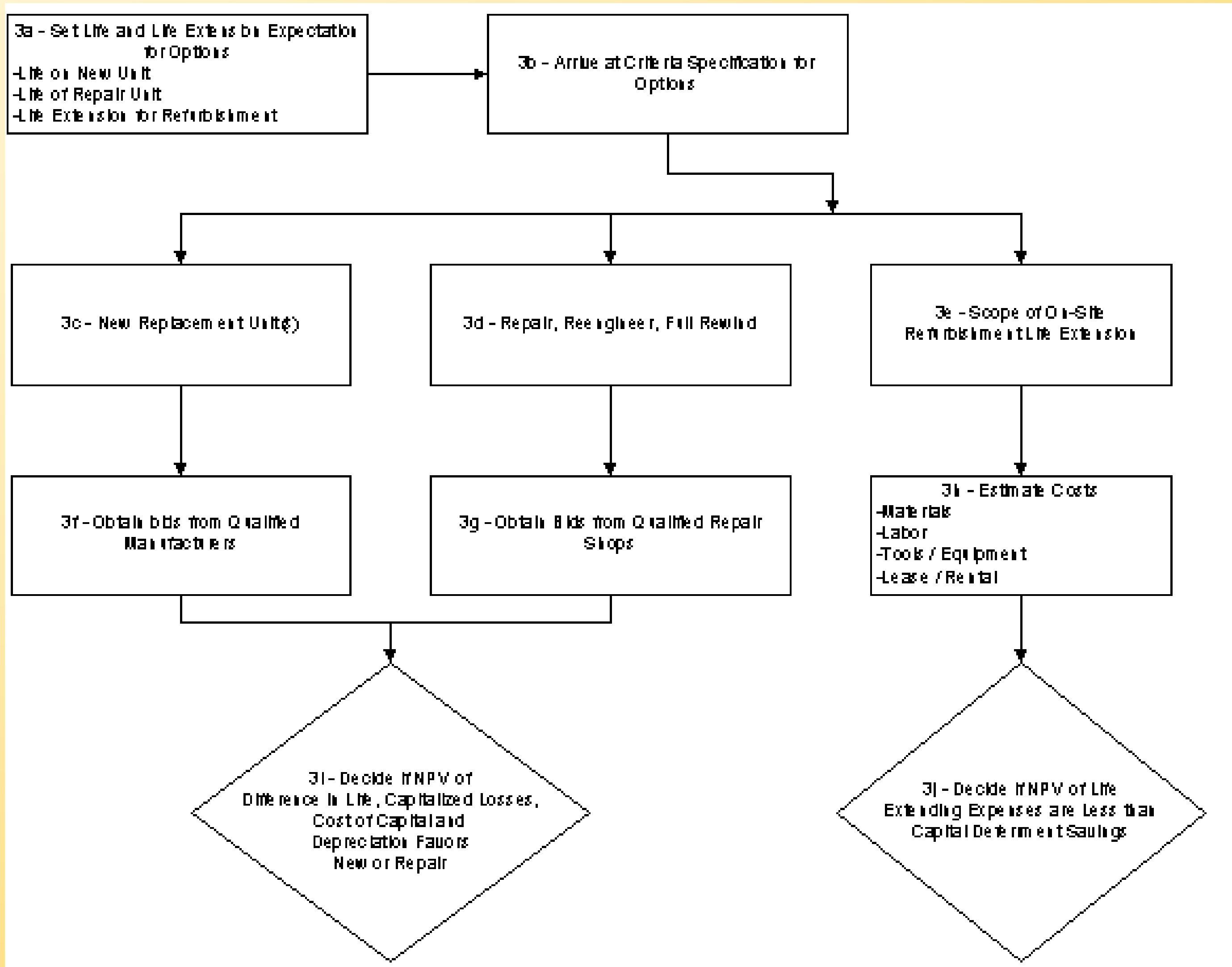
Unit Specific Investment Methodology



- **Cost comparison can only be performed if all the above cost considerations are available and make economic sense**
- **Least-cost alternative is nearly always the major deciding factor**
- **An evaluation that considers all factors will provide a high level of confidence that the right decision will be made**

Phase 3

Unit Specific Evaluation



Unit Specific Evaluation

Set Life Expectation for Options

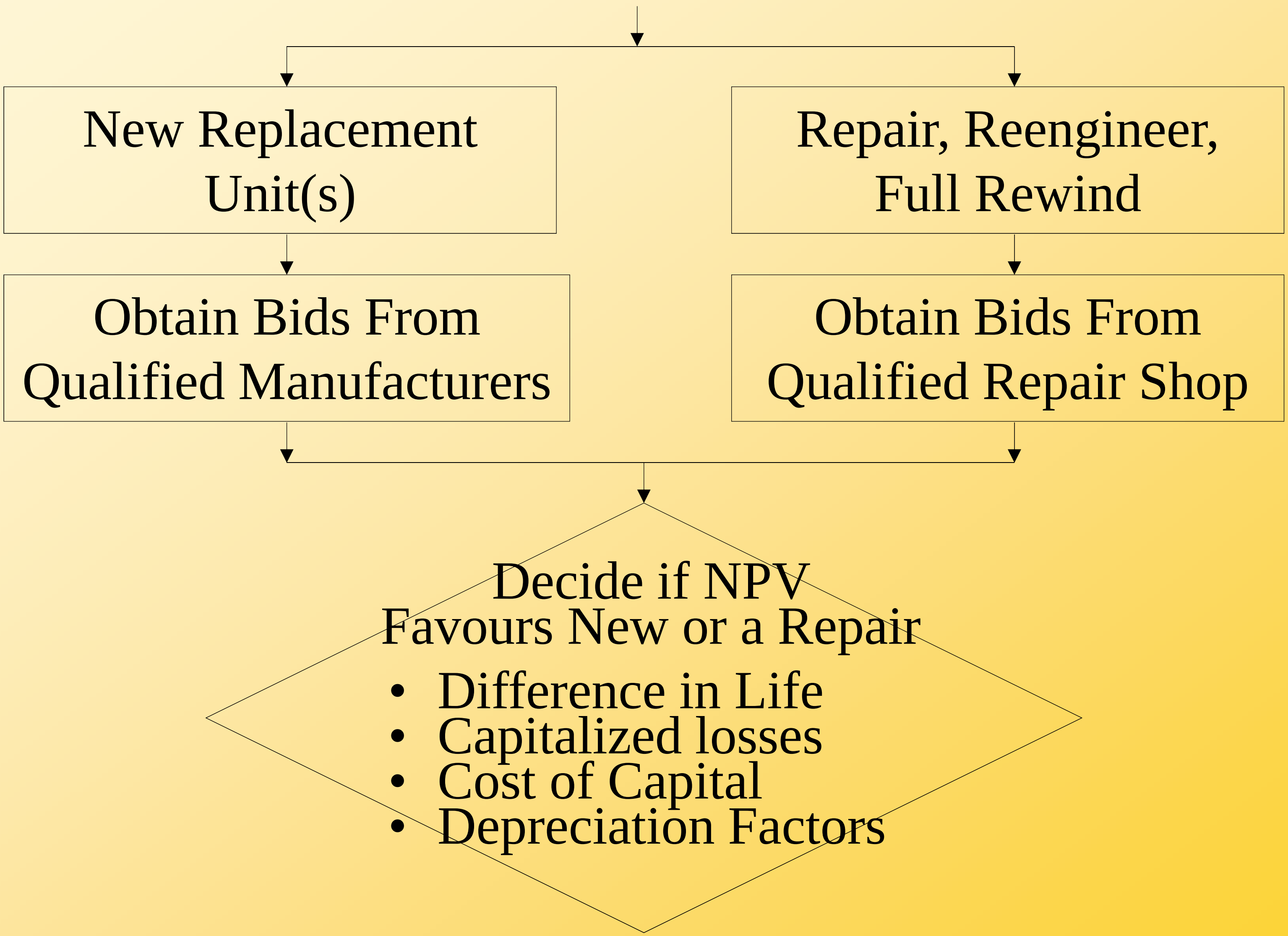
- Life of New Unit
- Life of Repair Unit
- Life Extension for Refurbishment

↓

Arrive at Criteria Specification for Options

- **Assign a value to the anticipated life that can be expected in the repair or refurbishment process in order to make a meaningful NPV calculation**
- **Written specification for on-site refurbishment and/or off-site repair must be prepared to make sure that all costs are known up-front**

Unit Specific Evaluation



Unit Specific Evaluation

Scope of On-Site
Refurbishment Life Extension

Estimate Costs

- Materials
- Labour
- Tools / Equipment
- Lease / Rental

Decide if NPV
of Life Extending Expenses
are Less than Capital
Deferment Saving

Example of application for Repair vs. Replacement

- **Method used: Average annual discounted cost**
- **Represents capital and maintenance expenses during an assumed period of 'N' years**
- **Numerical example:**
  - **Cost of new transformer 800 000**
  - **Cost for complete refurbishment 380 000**
  - **Core losses: Rebuild: 85kW, New: 35kW**
  - **Load losses: Rebuild: 360kW, New: 300kW**
  - **Average load on transformer 0.6**
  - **Interest rate 11%**
  - **Expected life duration for Rebuild 30 years**
  - **Expected life duration for New 55 years**

Replacement / Rebuilding Cost Calculation

Average annual discounted cost =	***CR***
Cost of rebuilding (or Cost of replacement)	C_R
+ Cost of losses	$+(\Delta P_0 + f^2 \Delta P_{CU})\, 8760kj \, \frac{(1+p)^N - 1}{p(1+p)^N}$
+ Cost for a new transformer after N years (in case of rebuilding)	$+Kinw \, \frac{1}{(1+p)^n}$
+ Cost of power not delivered during a failure	$+ PendPn f knen8760 \, \frac{(1+p)^N - 1}{p(1+p)^N}$
+ Maintenance Costs	$+Kma \, \frac{(1+p)^N - 1}{p(1+p)^N}$
- Residual value	$- Kscr \, \frac{1}{(1+p)^n}$

Cost for "New" transformer

Average annual discounted cost =	Cr_{new} = € 1 081 841
Cost of rebuilding (or Cost of replacement)	800 000
+ Cost of losses	$+(35 + 0.6^2\,300)\,8760 \cdot 0.025\ \dfrac{(1+0.11)^{55}-1}{0.11(1+0.11)^{55}}$
+ Cost for a new transformer after N years (in case of rebuilding)	*Not applicable for new transformer*
+ Cost of power not delivered during a failure	*Failure do not limit energy delivered* *knen = 0*
+ Maintenance Costs	*Maintenance cost is the same for both scenario*
- Residual value	*neglected*

Cost for “Rebuild” transformer

Average annual discounted cost =	Cr_{new} **= € 820 733**
Cost of rebuilding (or Cost of replacement)	**380 000**
+ Cost of losses	$+(85 + 0.6^2\, 360)\, 8760 * 0.025\, \frac{(1+0.11)^{30} - 1}{0.11(1+0.11)^{30}}$
+ Cost for a new transformer after N years (in case of rebuilding)	$+ 800\,000\, \frac{1}{(1+0.11)^{30}}$
+ Cost of power not delivered during a failure	***Failure do not limit energy delivered*** $knen = 0$
+ Maintenance Costs	***Maintenance cost is the same for both scenario***
- Residual value	***neglected***

Repair vs. Replacement Decision Process

- **Ratios of the average annual discounted costs are:**
  - **C_{Rnew} = € 1 081 841**
  - **$C_{Rrebuild\text{-}new}$ = € 820 733**
- **Rebuilding the transformer enables to save approximately 24%**
- **In regard to investment cost, rebuilding require only 48% of the money needed to purchase the new transformer.**

For more information consult Cigre Brochure 248