Session 9

Paper 4

WHAT MAINTENANCE IS WORTHWHILE AND WHEN

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Introduction

Northern Ireland Electricity plc has been conducting a review of maintenance strategy requirements (“What maintenance & when?”) as part of a radical realignment of the business along Asset/Network Management lines. Historically, maintenance has been based on fixed time intervals, with heavy reliance on equipment experts and a culture of “keep the lights on, whatever the cost”. While the latter objective remains clearly attractive, it is now tempered by a more risk-based appreciation, with business drivers that include service quality, cost, safety, environmental responsibility etc. These, plus the increasing regulatory pressures, require a much greater focus on auditable justification for what is done, and a shift from “fire-fighting” to a planned, cost/risk based strategy.

The MACRO project: cost/risk optimisation

The international MACRO project (European EUREKA project EU1488) has, for the last 3 years, been busily collating the experiences and best practices of many industries in cost/risk trade-off decisions. In addition to the development of innovative technical methods, MACRO is generating procedural guidance and training programmes to implement risk-based management techniques. High among these are the procedure guidance notes for reviewing or setting maintenance strategy. RCM, TPM or other acronym-packaged frameworks have emerged to provide some basic rules and principals, but they rarely cover the full spectrum of requirements. The MACRO project has assembled cross-industry observations and recommendations regarding best practice and the use of a *combination* of tools (such as Function & Criticality Analysis, FMEA, RCM and optimisation methods). The following section describes some of the generic rules, problems and their solutions.

Mixture of solutions needed

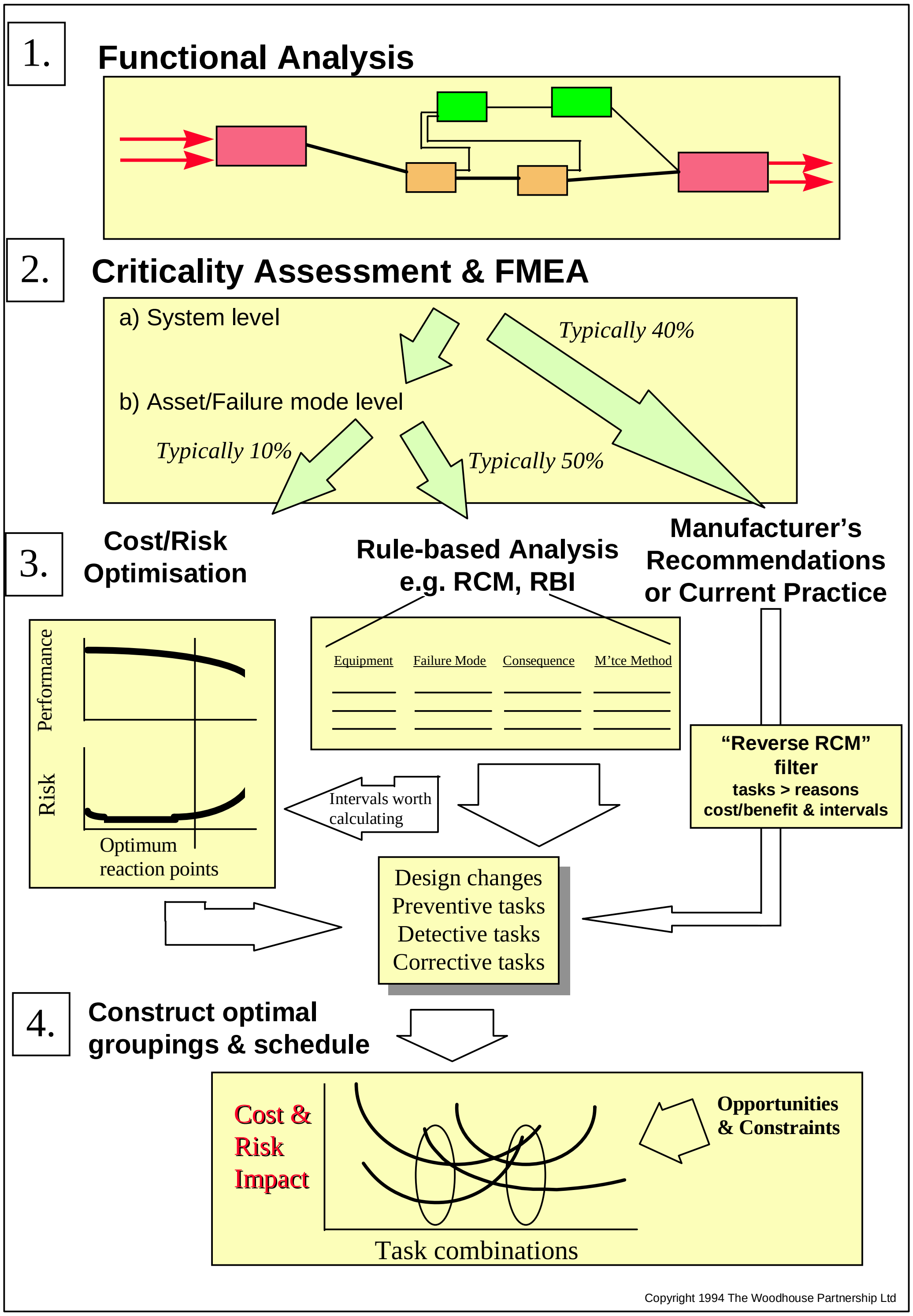
The key recognition within all MACRO companies was the need for a mixture of methods to determine “what work is worth doing and when”. No single formula yet on offer was found to be suited to different industries, or even to different processes, plant types or departments within the same company. The depth of analysis effort, and the value-for-money of such analysis, is clearly dependent upon the importance of arriving at the correct strategy. Criticality filtering of the systems, equipment and failure modes is vital to avoid ‘analysis paralysis’ and loss of direction. Visible return for the effort is also essential to maintain enthusiasm and management support for any systematic initiative. The 6 drivers that were agreed to have significance within NIE are

- Operational costs
- Repair Costs
- Customer minutes lost
- Safety Impact
- Environmental Impact
- Public relations (Shine)

The values created for these needed to be related to the probability of the incident occurring. For each event, failure rates as well as consequences are needed. All possible failures are then scored. The total score represents the system’s risk or criticality. For overhead line on the distribution system, the main driver is Customer Minutes Lost. This information can be used to prioritise the order in which refurbishment work is carried out on the overhead system. NIE has used this type of information in the past to prioritise overhead line work, however this study expanded the criticality to cover substation plant also.

The overall flowchart that has emerged from the MACRO team is one of multi-level analysis. At the top end of the criticality scale, for perhaps 5-10% of the most vital corporate functions, quantitative risk and performance analysis is warranted. For the next 40-60% of ‘core business’ activities, template and rule-based methods (such as RCM) are more appropriate. At the lower levels of process criticality, not even the simple tabulated questions and FMEA work are worthwhile - a cruder but quicker ‘filter’ is required. Figure 1 shows the overall flowchart up to the point of individually identified and justified maintenance tasks.

Figure 1. Combination of methods in “what maintenance & when?”



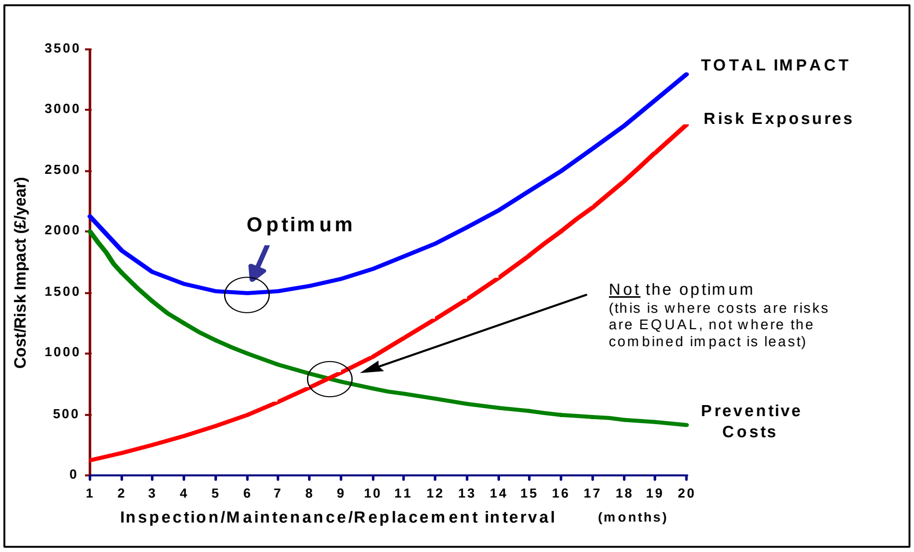
Maintenance Strategy Selection ("What type of maintenance?")

The logic embedded in RCM and TPM are unarguable – they are common sense developed into a set of "rules". For example (from the RCM arena), if the equipment failure mode shows warning signs which can be detected, and the failure consequences are significant, then a condition monitoring programme is recommended. If the failure is tolerable, unpredictable and not worth preventing, then an "on-failure" repair policy is appropriate. Similarly, from the TPM environment, operator responsibilities for equipment monitoring and cleaning are obvious common sense. The problems arise in that "common sense" is not so commonly applied. We are faced with a wide range, and incomplete knowledge, of potential failure modes, and considerable uncertainty about failure probabilities and consequences. The MACRO output includes selective use of components of RCM, TPM, RBI and other structured thinking 'formulae'. Basically, the more critical or complex the subject, the more detailed and structured should be the decision-making process. This endorses the requirement for greater auditability in justifying what should be done or spent, when *and why*. The more important the decision, the greater the requirement for demonstrating that the conclusion is appropriate.

Cost/Risk Optimisation ("How much preventive maintenance?")

The first concept that needs clarifying is the meaning of "optimum". In areas where there are *conflicting interests*, such as pressures to reduce costs at the same time as the desire to increase reliability/performance/safety, an 'optimum' represents some sort of compromise. It is clearly impossible to achieve the component ideals - zero costs at the same time as total (100%) reliability/safety etc. Higher reliability costs money, or, to put it the other way around, to spend less money we must choose what *not* to do or achieve. The inevitable trade-off can be drawn graphically (see figure 2), but we must be careful with the labelling.

Figure 2. Optimum = minimal Total Business Impact

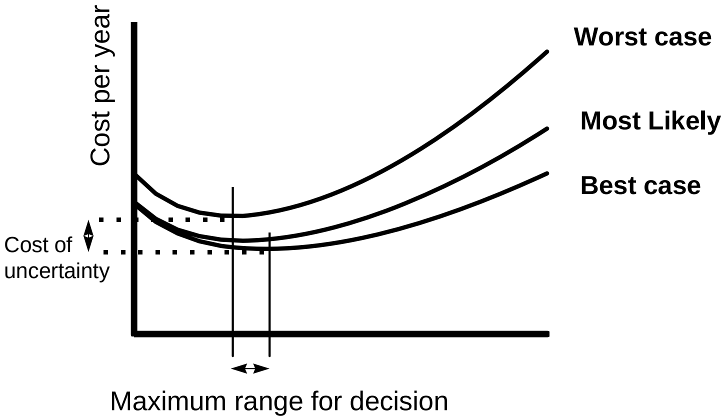


The next major issues are the lack of relevant data, and the complexity of the interactions (very few real cases can be simplified into just a preventive task versus risk of just one failure mode). Risks are difficult to quantify, and failure modes interact with each other ("infant mortality" or "maintenance-induced failures" affect the chances of experiencing age- or usage-based deterioration). Structured thinking is vital in this area, and the horrors of reliability mathematics need to be handled in the face of considerable data uncertainty. The first of these (a structured approach to describing the problems) is relatively easy to construct and introduce: if we group them by the types of questions that need to be asked, there are only 5 reasons for maintenance:

- **Reliability/Risk** (the maintenance reduces the probability and/or the consequences of specific events such as equipment failures or safety incidents)
- **Efficiency** (reduces operating costs or raises levels of performance or quality)
- **Lifespan** of asset (prolongs life, defers capital expenditure: eg. lubrication, painting)
- **Compliance** (legal requirements, over and above any self-interest in risk control)
- "**Shine**" factors (public image, employee morale, welfare & other intangibles)

Under each of these titles, specific questions and templates exist for quantifying the potential benefits from maintenance. Of course the numbers are often not available – "engineering judgement", experience and range-estimates are often the best information that can be obtained. Any number-crunching must take account of this uncertainty – and demonstrate which bits of information are important to the decision, and which make little or no difference. A "what if?" approach is essential, where extreme interpretations can be considered to see if different assumptions make any difference to the optimal strategy. This reveals what information is worth collecting in the future – a valuable 'spin-off' that solves a common secondary problem ("what data should we be collecting?").

Figure 3. Using range-estimates to calculate optimal strategies



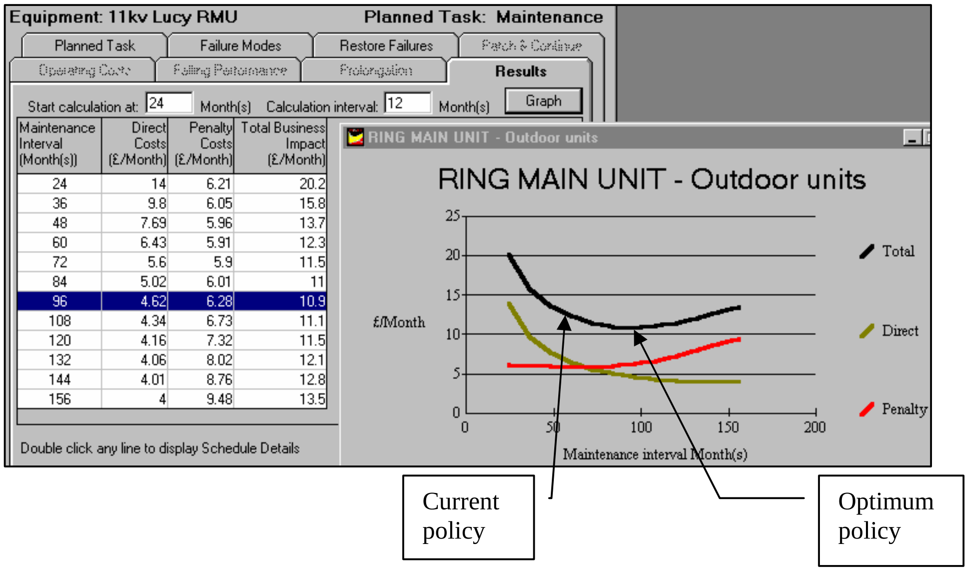
The nasty maths ("cost/risk trade-off")

Risk implications for different maintenance strategies, *or different combinations of maintenance strategy* are difficult to calculate. We must be able to handle various probability patterns, *interacting* risks, a variety of failure consequences and the degree of success of preventive actions. Whatever the shape of the "bath-tub" curves (i.e. whether or not it looks like a bath), it is difficult to quantify the residual risks that would exist under different maintenance strategies. The maths are well known in academic circles but they involve lots of integral and differential calculus and, to date, have only been applied in rarefied cases, where there is lots of data and a dominant failure mode, which is usually random. The MACRO project has made some radical advances in this area, creating software tools to perform "what if?" calculations with a great depth of potential complexity. The APT-MAINTENANCE™ tool can evaluate maintenance tasks in the environment of multiple failure modes, performance profiles, life expectancy impact and compliance/shine constraints. It can handle up to five simultaneous patterns, each comprising mixtures of deterioration, maintenance-induced failures and random events, and each with different costs and consequences. This has proved ample for the evaluation of all realistic bundles of planned maintenance activity.

Ring Main Unit Example – Preventive vs Corrective Maintenance

The Lucy FRMU was selected as an example for study, and the FMEA methods used to identify the principal failure modes being addressed by planned maintenance (PM). The planned maintenance workscope was identified to include replacement of lid and gaskets, oil replacement, inspection and check operation. The current PM interval is 5-years. Customising of maintenance strategy could easily consider different RMU designs/manufacturers, coastal/inland locations, or alternative maintainers/quality control methods; each requires a simple "what if?" change to the basic model.

Figure 4. RMU Planned vs Unplanned Maintenance



Equipment: 11kv Lucy RMU **Planned Task: Maintenance**

Start calculation at: 24 Month(s) Calculation interval: 12 Month(s)

Maintenance Interval (Month(s))	Direct Costs (£/Month)	Penalty Costs (£/Month)	Total Business Impact (£/Month)
24	14	6.21	20.2
36	9.8	6.05	15.8
48	7.69	5.96	13.7
60	6.43	5.91	12.3
72	5.6	5.9	11.5
84	5.02	6.01	11
96	4.62	6.28	10.9
108	4.34	6.73	11.1
120	4.16	7.32	11.5
132	4.06	8.02	12.1
144	4.01	8.76	12.8
156	4	9.48	13.5

Double click any line to display Schedule Details

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Risk-Based Inspection ("what do we monitor, how often?")

The evaluation and optimisation of condition monitoring activities requires slightly different questions to be asked, and calculations to be applied. There are two families of benefits to be quantified: the *predictive* maintenance objectives, with monitoring of key symptoms to pick up warning signs, and *detective* maintenance involving 'failure finding' or testing for hidden failure modes. Some inspections even achieve a combination both benefits. The structured thinking, and "what if?" maths, need to reflect these components. APT-INSPECTION™ is the MACRO tool for exploring optimal inspection, condition-monitoring and testing strategies.

Pole Monitoring Example - Risk-based Inspection

NIE has a pole population of approximately 500,000. Cost is the main driver for their monitoring and reliability. Is it cheaper to let them fail in service or replace them in a planned manner? Costs for failure of a pole in service, as well as the cost of the inspection and planned replacement, are required.

Circuit unavailability is expressed in units Customer Minutes Lost (CML). This is more than the cost of a unit of electricity not sold. NIE invests a considerable amount trying to improve quality of service. There is a 'Shine' factor associated with customer impression, and the Regulator, Government and the city are interested in the number of CML's that occur on an annual basis. To take this into account, we decided to base the cost of a CML on the amount of money NIE is investing to prevent faults occurring.

Our current practice is to replace poles that are suspected of decay or have any decay present. The study of pole inspections assumed that we would inspect a pole and, if the pole is borderline, we would "purl test" it to quantify the residual strength. Poles which had some decay present yet retained 75% residual strength would then be treated with a preservative and survive for an additional 5 years. Our current policy is a 5-yearly inspection for wood poles.

The uncertainty in Rate of Deterioration was taken into account by covering the extremes in deterioration that have been observed on the NIE network. The initial model based on expectations for overhead lines, assumed a pole survives at least 20 years with an average lifespan of 40 years. This gave us a patrolling interval of 8 years. Another interpretation, based upon historical data, reflected 13 % of poles decaying over 30 years as an average deterioration, and worst case within 15 years. This gave us an optimum patrolling frequency of 10 years.

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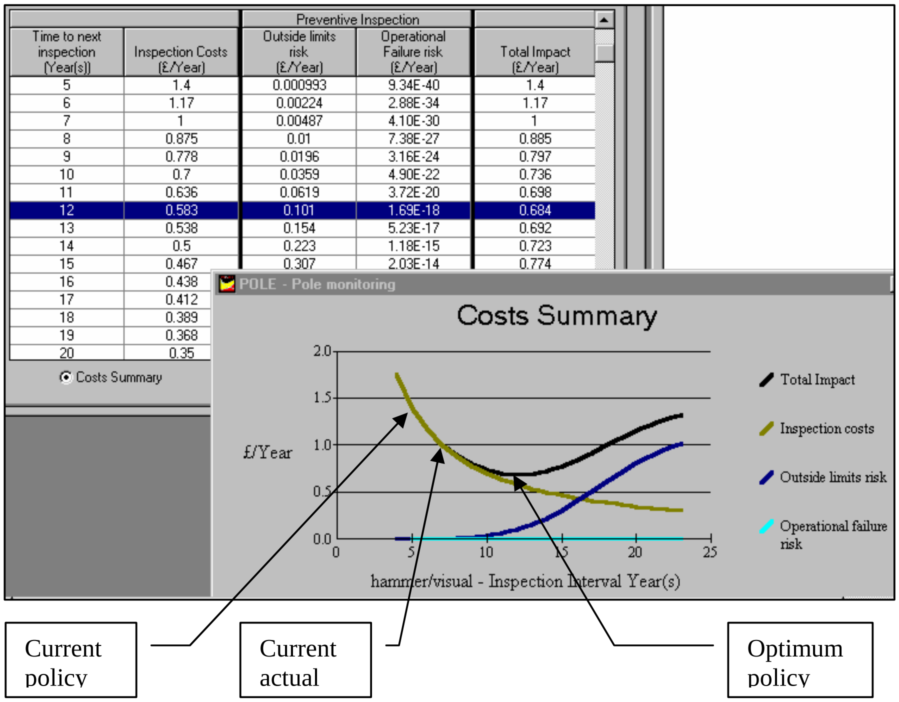
The study results give an optimum time span to carry out the inspection of wood poles and the total cost/risks of such a maintenance policy. It also shows additional cost incurred for deviating from this optimum by extending or shortening the time span. Uncertainty in the impact of failure had the largest impact on the result.

Figure 5. Optimal inspection strategy



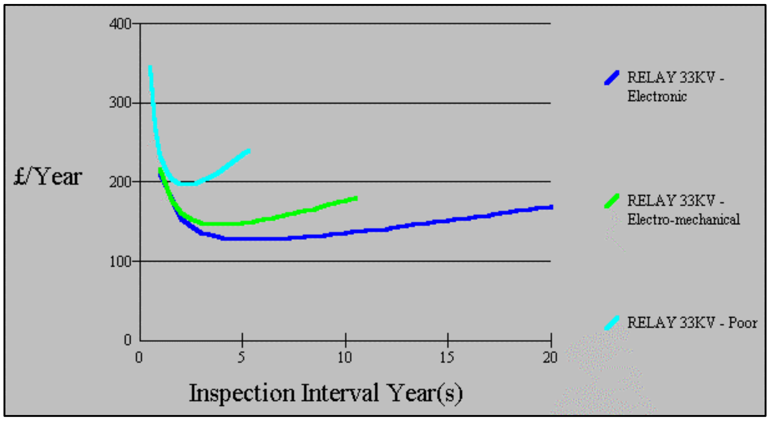
		Preventive Inspection		
Time to next inspection (Year(s))	Inspection Costs (£/Year)	Outside limits risk (£/Year)	Operational Failure risk (£/Year)	Total Impact (£/Year)
5	1.4	0.000993	9.34E-40	1.4
6	1.17	0.00224	2.88E-34	1.17
7	1	0.00487	4.10E-30	1
8	0.875	0.01	7.38E-27	0.885
9	0.778	0.0196	3.16E-24	0.797
10	0.7	0.0359	4.90E-22	0.736
11	0.636	0.0619	3.72E-20	0.698
12	0.583	0.101	1.69E-18	0.684
13	0.538	0.154	5.23E-17	0.692
14	0.5	0.223	1.18E-15	0.723
15	0.467	0.307	2.03E-14	0.774
16	0.438			
17	0.412			
18	0.389			
19	0.368			
20	0.35			

Protection Relay Example – Failure Finding

The protection equipment for 33kV systems has been classified into four groups: “poor”, “electro-mechanical”, “electronic” and “distance”. For the first three, the failure modes and defect discoveries have been recorded and counted. These latest test results were used to provide the data needed for the study. The current intention is to perform annual testing on the worst groups (“poor” and “electro-mechanical”) and 3-yearly testing on the remainder. However the results revealed that different intervals were appropriate:

Relay group	Current policy	Optimal policy	Cost/risk Improvement
Poor (300 units)	annual	2-yearly	£9,000/yr
Electro-mechanical (4,500)	annual	3-yearly	£220,000/yr
Electronic (800)	3-yearly	6-yearly	£8,000/yr
		TOTAL:	**£247,000/yr**

Figure 6. 33kV relay testing results (Total Cost/Risk Impact curves)



Rule-based strategies (RCM, sRCM, RBM, TPM, some types of RBI)

Various flavours and industrial variations have evolved. RCM, with its origins in the civil aircraft industry, is a specific rule-set suited to environments where large numbers of components and failure modes exist, but relatively clear failure consequences or deterioration timescales allow black-and-white decisions on prevention, tolerance or condition monitoring. TPM provides a wider umbrella, combining continuous improvement activities, operator/maintainer responsibilities, overall equipment performance levels and attention to detail. It lacks, however, the tools to determine the individual maintenance decisions. Templates, rule-sets and organisational considerations are vital to address the high volume, core business areas. The costs and efforts of fully quantified risk-based analysis, with all the "what if?" testing of uncertain data, would be prohibitive. Some compromise on precision and accountability is acceptable in order to achieve the volume of results.

So far, RCM and its variants have been favoured by complex process and downtime-critical industries, while TPM has focussed largely on the manufacturing sector, and the US developments in RBI (API RP580/1) are emerging from the petrochemical industry. The cross-fertilisation is beginning, however, and the MACRO project is developing a set of guidance notes on selective use of components in different circumstances. For example, RBI is useful for maintenance of static equipment, whose failure modes are dominated by corrosion, erosion or other forms of passive ageing. For complex mechanical plant or networked processes, where there is a wide range of failure modes and consequences, RCM rules are valuable to separate out the appropriate treatments (design changes, preventive, predictive and failure-finding tasks or operate-to-failure). Where many of the failure modes exhibit warning characteristics, and operator personnel are always or regularly attending, then "first-line" condition-based maintenance is obviously appropriate – and education or multi-skilling are key considerations (so TPM is best).

Sanity Check of low-criticality maintenance (REM)

At the bottom end of the criticality scale, the analysis effort and manpower required to consider individual failure modes and consequences (even at an RCM/RBI level of detail) are simply not worthwhile. A faster, cheaper (and cruder) method of setting maintenance strategy is more cost-beneficial (see Figure 1). The MACRO guidance here takes the form of a pragmatic review or existing or recommended strategies. Two tests are applied in this "sanity check":

a) there is a failure mode that could be prevented by the proposed work
b) the preventive work is cheaper than failure consequences (and what would happen if we doubled the interval?)

REM is effectively a form of reverse-direction RCM thinking: it takes a 'solution' and works backwards to check that a suitable reason exists. Given that such methods would be applied only to low criticality areas, the consequences of error are, by definition, small. In this area in particular, manufacturers' recommendations will tend to be excessive and such a screening will generally filter out a proportion of unnecessary work. Of course, such filtering does not identify the need for new or additional work – this requires a jump to the normal-direction methods (RCM, RBI etc.) of identifying the threats, classifying them and determining what preventive work is appropriate.

Maintenance Scheduling ("bundling the tasks into work programmes")

Whatever the route to identifying necessary maintenance tasks and appropriate intervals, there remains a co-ordination and scheduling stage (step 4 in Figure 1). Individual tasks must be clustered into a programme of work to minimise equipment downtime, achieve whatever efficiency savings are possible in resource utilisation, fit into operational windows or background constraints (such as seasonality, environmental or safety legislation etc.) and strive to maintain ease of administration or work control. This typical "planner's nightmare" is being addressed by a specific working party within the MACRO project. The preliminary research has indicated that very considerable improvements can be made by relatively simple structured methods, and that even greater advances are possible if some semi-automatic "what if?" analysis is available. Compared to a human planner, the cost/risk optimisation techniques achieved a 28% increase in system availability *at the same time as* a 22% reduction in total costs/risk exposure. This work was discussed in a paper presented by The National Grid Company at MAINTEC 98.

Conclusions

The studies confirmed that a mixture of techniques is needed for determining "what maintenance is required and when" in an electrical distribution environment. These are summarised below. The objectives of the study were fulfilled and a maintenance strategy process is being developed as a result. A significant 'spin-off' from the pilot studies was the identification of six-figure annual savings in cost/risk from just 30 mandays of analysis.

Method	Objectives	Observations	Conclusions
Functional analysis (11KV OH line & substations)	Navigable map of which assets do what, and why.	Not particularly useful due to close (1:1) link between equipment and functions already	Use existing circuit and equipment hierarchy to prioritise studies (criticality-based)
Criticality assessment (HV switchgear, LV distrib. circuits)	Prioritise which assets and/or functions need what depth of analysis (+ many other uses)	Not currently available: urgently required for many reasons. Prototype tested on 2 asset groups.	Refine and apply the prototype method and encourage broad application/usage
FMEA (11KV OH line & Substations)	Collate and list possible reasons for maintenance (failures and their consequences)	Valuable activity, particularly for complex assets. Important audit trail, needs ongoing data maintenance.	Apply as part of all studies leading to RCM or C/RO. Obtain database to hold/update the information.
RCM (33/11KV and 11KV/LV substations)	Apply internationally recognised logical ruleset to determine appropriate type of maintenance strategy	Heavy time requirement, sometimes not needed if assets are static/simple or have only a few failure modes.	Use on complex equipment types only, or cases where many failure modes or unclear maintenance tasks.
C/RO (Lucy FRMU 11KV ring main units)	Find optimal cost/risk combination for preventive maintenance, reliability, performance, lifespan etc.	Surprisingly successful given acknowledged poor data availability. Conceptually complex but widely applicable.	General implementation with carefully controlled usage (trainees only). Most valuable application to high-criticality or large population assets .
RBI (OHL inspection, pole monitoring, 33KV protection testing)	Ditto, for inspections, condition monitoring and functional testing activities	Only became available part-way through pilot project yet provided clear risk-based justification and optimal intervals. Simpler concepts than C/RO.	ALL inspection and testing intervals should be evaluated this way (esp. O'Head Line & protection equipment). Real potential for regulator negotiations.