Risk-based Decision-making in Maintenance, Inspection, Spares and Asset Renewal.

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Abstract

MACRO is a multi-industry, UK government-supported joint venture (European 'EUREKA' project EU1488), that has developed guidance and tools for better cost/risk evaluation and Asset Management decision-making – particularly when hard data is limited or unavailable. It has brought together the complex technical aspects of reliability engineering, risk-based analysis and asset deterioration modelling with the commercial factors, human issues and psychology, and the capture/usage of tacit knowledge to compensate for data uncertainty. This paper focuses on some of the resulting 'best practice' methods, analytical tools and the results that have been generated.

The boundaries of the project were chosen to meet the perceived priorities and a practical development timeframe (5 year programme). Over 40 specific areas of decision-support requirements were explored, each in terms of the disciplines, business value-for-money, sources of data and knowledge that are required, and the underlying commercial/risk mathematics that should be incorporated. These topics were grouped into the following areas:

- **Asset Life Cycle Costing**: the hands-on tools for project evaluation, equipment replacement, life extension, change control & modifications.
- **Maintenance Optimisation**: evaluating preventive maintenance strategies, optimum intervals, legal/safety compliance, environmental constraints.
- **Inspection & Condition Monitoring**: setting inspection, monitoring & test intervals, optimal condition reaction points, cost/benefit of monitoring methods.
- **Work Grouping & Shutdown Strategy**: evaluating optimal task groupings, shutdown intervals and opportunities.
- **Materials & Resources**: cost/risk optimisation of slow-moving spares, consumables, supplier comparisons, materials pooling and alliances.

This paper introduces the generic approaches that were identified, and illustrates their usage in just two of these areas: *Maintenance Optimisation* and *Inspection/Condition Monitoring..*

1. INTRODUCTION & PROJECT SCOPE

The international MACRO project has been busily collating the experiences and best practices of collaborating organisations in many industries. In addition to the development of innovative technical methods, MACRO has generated procedural guidance and training programmes to implement risk-based management techniques. High among these are the procedure guidance notes for reviewing or setting maintenance & inspection strategy. Of course this subject has received a lot of exposure over the last few years - mostly focussing on particular ‘initiatives’ such as Root Cause Analysis (RCA), Reliability Centred Maintenance (RCM), Risk-Based Inspection (RBI)and Review of Existing Maintenance (REM)/Reverse-RCM, Total Productive Maintenance (TPM), Life Cycle Costing (LCC) and other acronym-packaged frameworks.

The MACRO developments have concentrated on innovation in some of the most difficult areas of all – how to make robust, auditable decisions when hard data is unavailable or incomplete. The development work took the form of a number of workstream, employing the leading experts in each field as well as pragmatic field personnel. Each team researched and reviewed existing best practices, and developed innovative “what if?” analytical tools, plus common sense guidance for navigating the problems, identifying the optimal solution, for the structured capture of existing knowledge and for the determination of what data is worth collecting in the future.

The primary workstreams were:

a) **Decision Navigator**: developing a master guidance (flow diagram) for selecting appropriate analysis techniques for different types of problem and decision. This has yielded an interactive MACRO Navigator web tool.

b) **Capturing ‘tacit knowledge’**: *how to ask the right questions* of subject experts, including capture of the inherent uncertainties, quantification of ‘intangibles’ and exploring the limits of credibility in their assumptions – all without ‘leading the witness’ and distorting the information during the process.

c) **Maintenance Strategy**: combining the best bits of various ‘good practice’ methods such as. This workstream has yielded the most comprehensive toolkit possible for fully quantified optimisation for **maintenance intervals**, taking into account multiple failure mode/risk profiles, efficiency degradation and life extension effects. This also includes the innovative developments in quantitative risk-based techniques for optimising condition monitoring strategies (**optimal inspection intervals**, **condition reaction points**) and for optimal **intervals for functional testing** of safety and standby equipment (hidden failure finding).

d) **Shutdown strategies**: optimising **work bundles**, **opportunities** and **shutdown intervals** for inspections, maintenance, modifications, equipment replacements and other project work.

e) **Spares & Purchasing Decisions**: determination of **what spares are worth holding**, in what quantities, which **supplier options** are best, **spares pooling** options etc. and, for medium/fast moving materials, the optimal **purchasing trigger point and quantities**.

f) **Capital projects cost/benefit/risk evaluation**: guided, quantified value-for-money assessment of different projects and change proposals – providing a common cost/benefit basis for **comparing dissimilar project types**, particularly when assumptions are uncertain and there are intangible factors involved.

g) **Whole life cycle optimisation**: the Life Cycle Costing concepts extended to include all aspects of operational risk, performance, deterioration, maintenance activities, **life extension options** and **optimal renewal or upgrade decisions**.

2. Generic lessons in optimisation

2.1. What is "optimal"?

One of the first important messages learnt in MACRO is how often we have, in the past, been aiming for the wrong target – thinking that the 'optimum' is the least cost, or the 'break-even' point, where risks justify an intervention because the level of risk equals the cost of the intervention. It takes a deliberate re-think to get an organisation to understand, and target, the *best combined mix* of costs plus risks. MACRO adopted the term "Total Business Impact" to describe this criterion, and participants have found this to be a very effective method for raising the debate above the individual vested (and conflicting) interests of different departments or affected individuals.

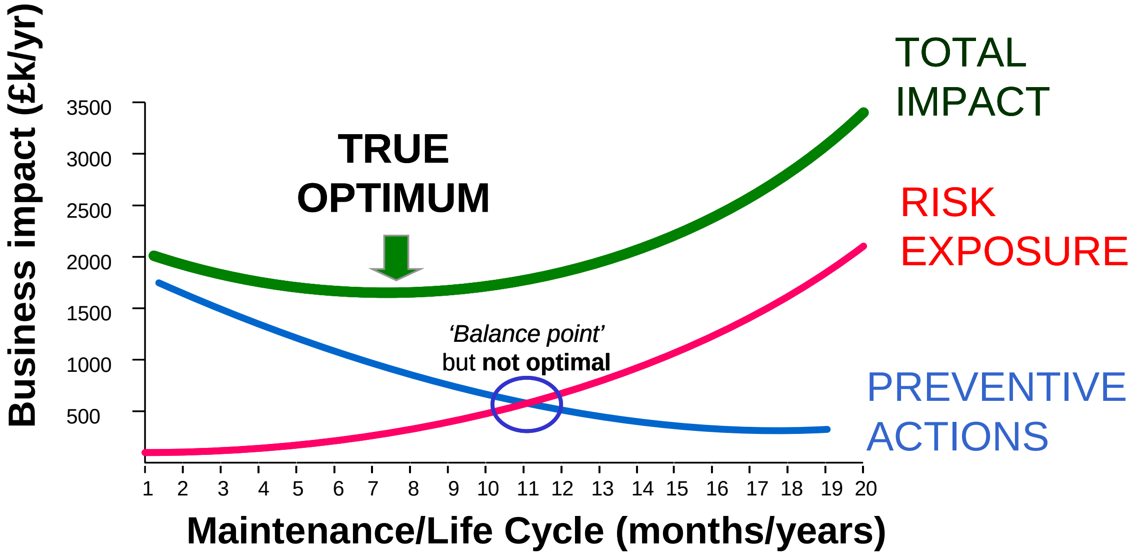


Figure 2. Aiming for the optimal Total Business Impact

2.2. Structured capture and use of tacit knowledge

The second big, generic message learnt was a combination of

- How to force the right questions to be asked
- Who to involve in each decision – always a cross-functional mix of affected individuals
- How to ask such questions in the right way (how to extract experience, expertise and tacit knowledge from subject experts)
- How to quantify uncertainty, and explore its significance (including identification of assumptions or data requirements that make a critical difference to the decision).

In summary, this involved some innovative psychology in phrasing the questions and some real-time "what if?" calculating tools to learn if and how each assumption influences the final optimal solution. Surprisingly this did not result in people 'engineering' the answer that they wanted – it proved almost impossible to force a given conclusion by distorting the inputs (the distortion required was usually self-evident and therefore not credible). The process of range-estimating and sensitivity-testing, provided it is done 'live' with the relevant contributors of information, yielded, in most cases, robust and transparent, business-justified cases for the optimal strategy – within a structured 1-2 hour period. This was proven even for extremely complex problems with wide boundaries of uncertainty and multiple options to consider. Furthermore, the optimal Total Business Impact is often found in a surprising area – historical practices, or subjective judgement, has been distorting the picture with significant cost/risk consequences.

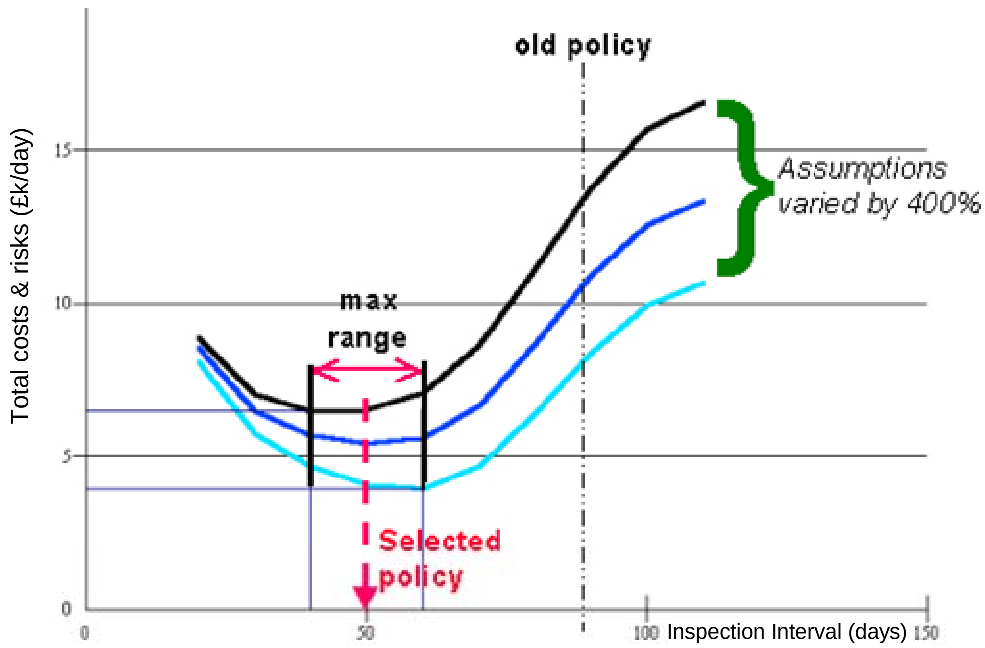


Figure 3. Use of uncertain data to determine optimal intervention point

3. MAINTENANCE STRATEGY PROCESS

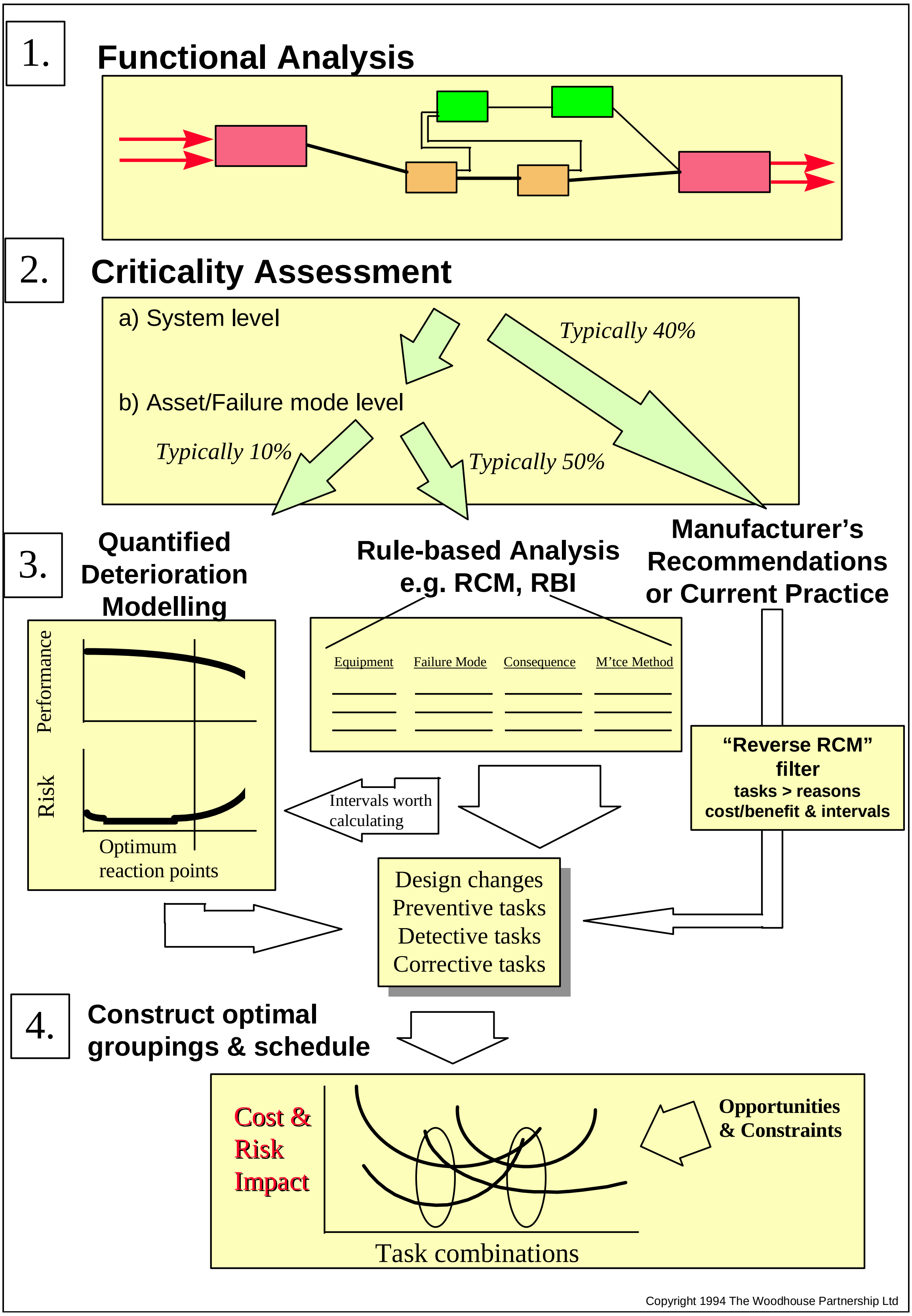
3.1. 'Horses for courses'

The first conclusion reached by the Maintenance Strategy working party 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 overall flowchart that has emerged from the MACRO team is one of multi-level analysis. Dependent upon *process or functional* criticality, differing levels of analysis effort should be applied. At the top end, 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 or RBI) 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. The process of consolidation and optimisation of an overall maintenance programme is the subject of a specific MACRO working party, which has developed dynamic optimisation methods for work clustering and shutdown strategies (“APT-SCHEDULE”).

Figure 1. Strategy methods depend upon Operational Criticality



3.2. Functional focus

In order to determine which physical assets are worth maintaining to what degree (and which are worth analysing to what level), a shift of emphasis is vital. Maintenance strategy has historically been directed at types of equipment. The same recommendations on maintenance work and intervals are issued, whatever the operational role or importance of that equipment. The service interval and task list for a Vauxhall Cavalier is the same, whether the car is just one available from the company vehicle pool, or is a doctor's sole means of transport! Clearly the consequences of breakdown can be very different – so the importance of reliability differs and the level of maintenance should be adjusted accordingly.

Despite the common horror stories of inappropriate application, one of the big advantages of RCM logic is that it considers equipment function and loss of function as important criteria. However, in its original form, RCM only attaches these characteristics as an attribute to the equipment. The whole asset list is reviewed and, for each piece of equipment, the functional failure, operational or other consequences and the failure modes are all employed to determine the appropriate maintenance strategy. Unfortunately, by this route, the analysis of each equipment's characteristics *has to be almost complete before it becomes clear whether it was worthwhile examining in the first place*. The team doing the review has to apply nearly the whole procedure to find out which items were worth reviewing at all! To allow an earlier filter and prioritising of such analysis effort, therefore, a clear understanding is needed of which systems do what, and what happens if they do not. This process mapping or 'functional breakdown' can shift the focus dramatically. Not only does it provide a means of prioritising the maintenance strategy studies, it also achieves a wider operational awareness (it can be a revelation to maintainers and operators alike) and invariably stimulates ideas for design or procedural improvement.

The methods for mapping equipment functions are similar to those employed in 'business process re-engineering'. However, the terminology and process (or systems) viewpoint may not be familiar to the operators and maintainers who should be involved in developing the map, so guidance and facilitation is usually needed. A summary of a simple level of Input-Process-Output diagramming suits many requirements. More detailed methods (such as the ICOM format, which separates out the Inputs, Constraints, Outputs and Mechanisms) are available - but the method is less important than the fact of considering operational requirements and failure likelihood/consequences first, and the necessary equipment (and its maintenance requirements) second. The underlying objective is to direct the costly analysis effort at the most important functions or core business of the organisation.

3.3. Criticality analysis

The commonly promoted versions of RCM focus firstly on equipment, and then its operational context, failure modes, consequences and maintenance requirements. The MACRO network has clearly concluded that this is wasteful and often results in duplicate consideration of identical or similar maintenance requirements, and low-value analysis of marginal equipment or failure modes. A common feature of successful implementations is the criticality-based priority or filtering of which systems, equipment and failure modes are worth analysing in the first place. This may not be formalised ‘criticality system’ but, if the review of maintenance requirements is to be systematic and/or will involve a wide range of personnel from different backgrounds, then a consistent and generally agreed ranking method is necessary. A survey of such methods, with practical applications guidance, has been prepared as one of the reference documents of the MACRO project.

The key feature of successful ranking methods is the combination of failure consequences (safety, economic, environmental or others) with the likelihood or frequency of failures. Degree of detail varies, along with the guidance and ‘weighting’ methods for scoring the different elements, however the combination (usually a multiplication of frequency and consequence) aims to prioritise the small-and-frequent among the big-and-rare. Several other learning points were also developed, such as the design tips for appropriate, quantified weighting of safety, environmental, commercial, reputational and other ‘intangible’ pressures.

4. Maintenance Strategy Selection

The MACRO project has developed structured methods to review maintenance requirements at each level of business criticality. These merge existing best practices with innovative improvements and tools. RCM and RBI logic, for example are incorporated in correct levels of critical usage (typically 30-40% of the cases), with supportive guidance on the evaluation of efficiency-oriented maintenance, lifespan-related tasks (such as painting or lubrication) and the cost/risk basis for setting inspection or maintenance intervals. A series of articles and case studies have been published about this approach, and innovative software (APT-MAINTENANCE & APT-INSPECTION) developed to support the quantified (cost/risk) evaluation of maintenance options.

4.1. Quantified risk-based maintenance

Once the process criticalities have been identified, the analysis of maintenance requirements splits into different levels of detail. For the few really vital processes (5-10% of all systems), the approximations and black/white assumptions of RCM or RBI (‘risk-based inspection’) are rarely sufficient to determine the optimal combination of operating and maintenance strategies. For example, RCM and RBI both require a clear and consistent definition of ‘functional failure’ - yet this is often a grey area in real life. What degree of deterioration do you choose to define as ‘unacceptable’? The level of risk that is worth taking, and the quality or performance that is achieved, or the life expectancy of the asset are often negotiable, and can be influenced by the amount and type of maintenance. In critical areas, the additional sophistication and data collection required to quantify such risk and performance trade-offs can be very worthwhile (see Appendix 1). MACRO field feedback has shown consistent scope for multi-million pound/dollar savings through such a quantitative approach. Examples range from painting programmes and lubrication schedules to major overhaul or shutdown strategies and inspection/test intervals.

4.2. Risk based Inspection

Another big area of quantitative analysis is the setting of inspection and condition monitoring strategy. Much work is going on in this area in the United States, albeit mostly concentrated on the monitoring of static equipment (vessels, pipes etc) on petrochemical plants (American Petroleum Institute RP580/581). The MACRO focus has been wider and more quantitative. A cost/risk balancing tool has been developed to evaluate optimal strategy in the light of various uncertainties (rate of deterioration, point of failure, quality of measurement etc.) and the early results of its application are extremely encouraging. Applications already proven include the condition monitoring of wooden poles (electricity distribution), corrosion monitoring of pipes and storage vessels, function testing of safety protection and standby equipment, and instrumentation. An example of such application is illustrated in Appendix B to this paper.

Regarding the *value* of risk-based study (instead of simpler, rule-based approaches), the MACRO team has performed some systematic comparisons: a sample of five condition monitoring strategies, arrived at by RBI guidance (following API RP580 procedure), were checked with the APT-INSPECTION analysis. Two of the five cases were found to be about right (+/- 20% of optimal timing), but one decision was a factor of 8x in error (the job should have been done at $1/8^{th}$ of the interval), and the others were not worth doing at all (the cost of the shutdown & inspection was greater than the risk it was addressing!). This cost/benefit evaluation and optimisation has yielded similar results in challenging current testing intervals for safety and standby equipment – sometimes showing that significantly more testing is justified, and in other cases, that current policy is not possible to justify by the risks involved.

5. Whole life cycle optimisation

MACRO has yielded a number of major innovations in the handling of life cycle costs, equipment renewal decisions and the evaluation of project alternatives that have different benefits horizons (where Net Present Value methods of evaluation are not suitable). APT-LIFESPAN has proven to be a significant step forward in the quantified evaluation of life cycle options, generating fully transparent ‘optimal’ life predictions (see Figure 3) and ‘what if?’ ability for many project, purchasing, operating and other strategies. The MACRO methodologies have extended to include upwards assembly of fully quantified work programmes – the best way of coordinating maintenance, inspection, capital projects, shutdown opportunities, constrained resources and ‘work bundling’. Appendix 3 shows how this is now being done.

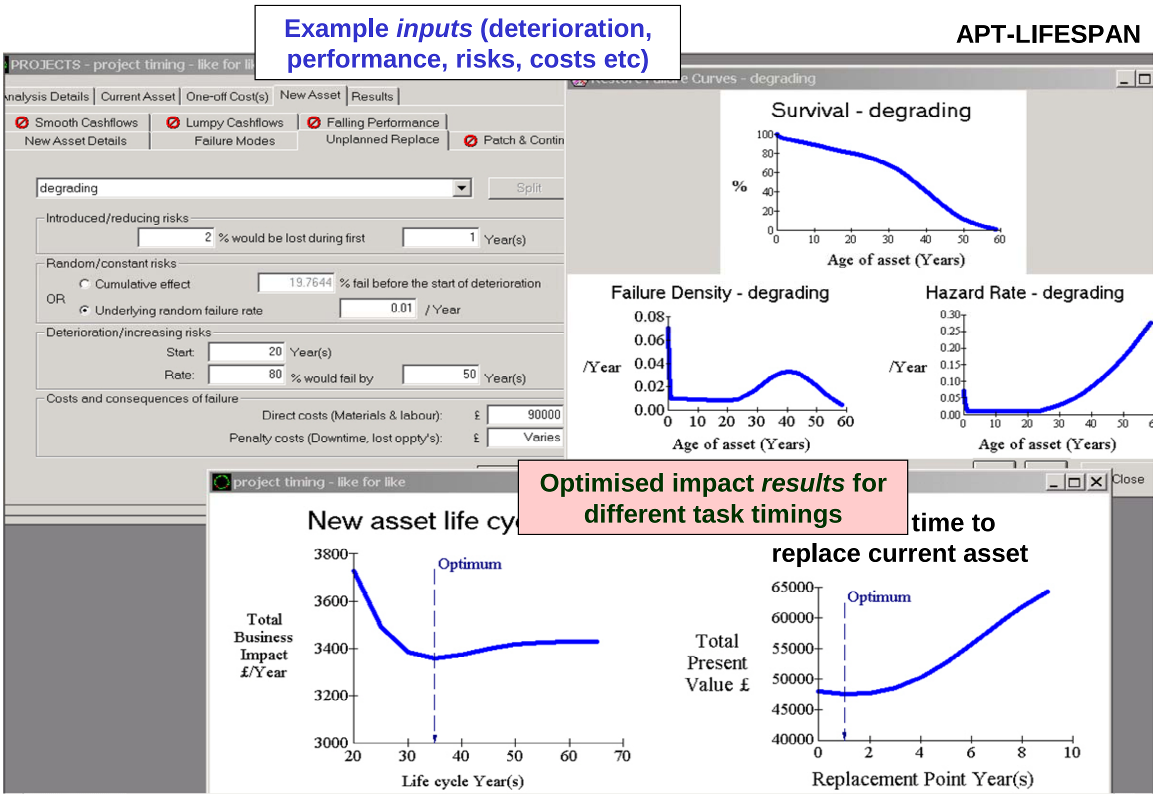
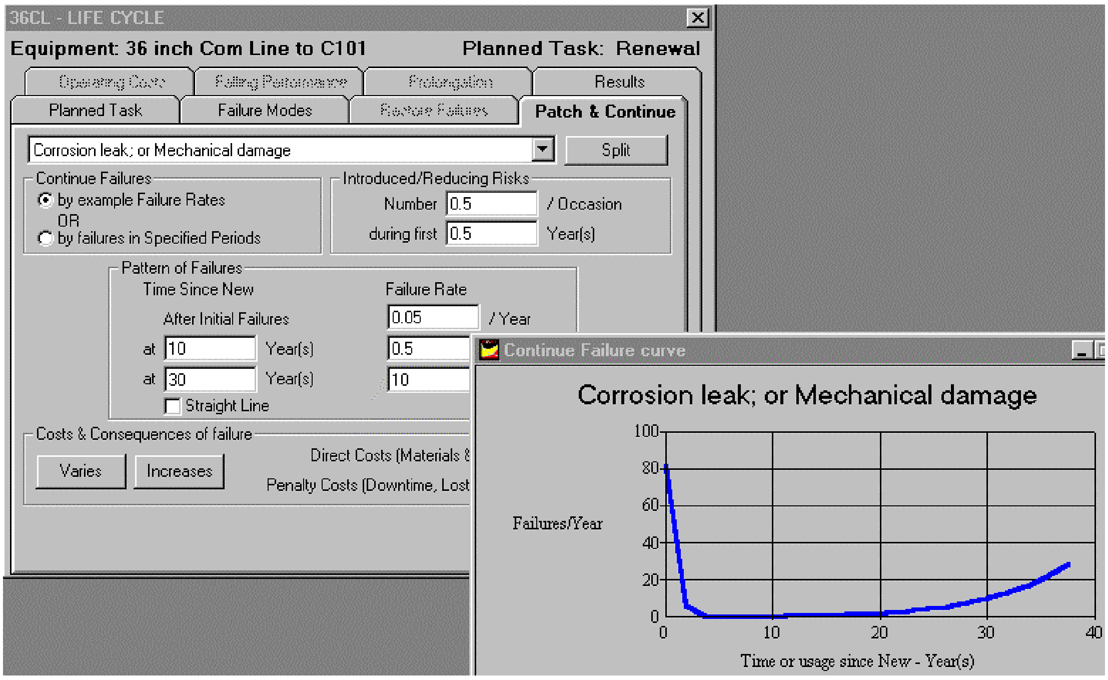


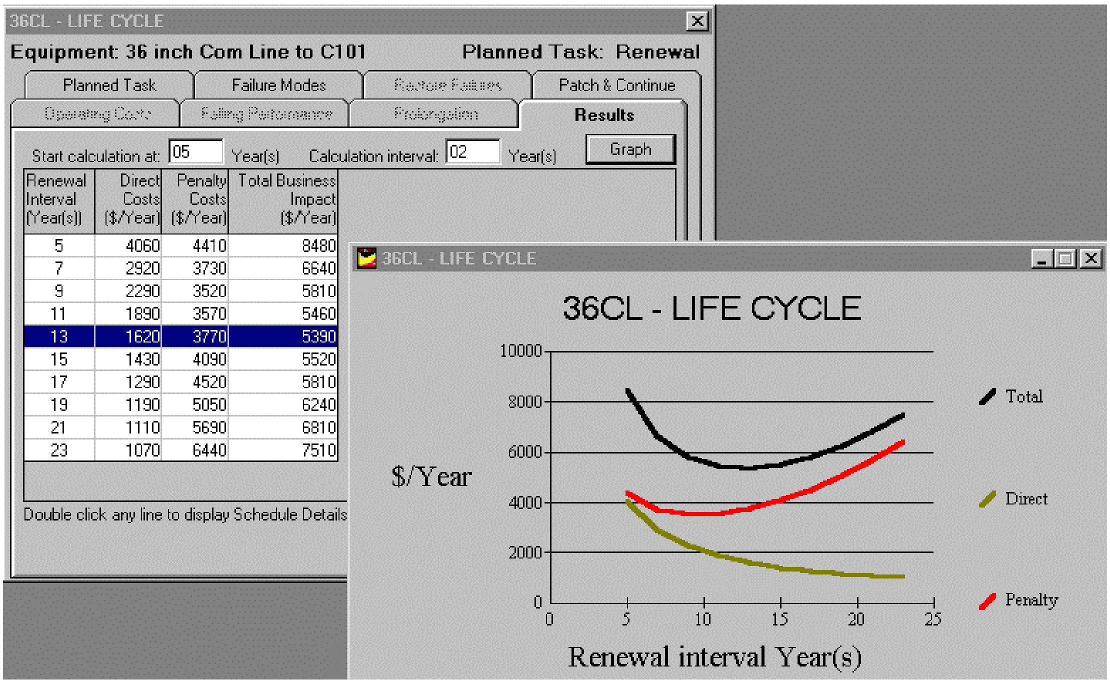
Figure 3 Life Cycle modelling to identify optimal equipment replacement timing

Appendix A: MAINTENANCE vs REPLACEMENT CASE STUDY

Reliability projections (assumptions) are range-estimated and combined with potential failure consequences and the estimated costs of planned maintenance or replacement. The uncertainty in is handled by sensitivity testing, showing that the decision to replace the pipeline at the 12-14 year point is robust, even in the light of widely varying assumptions. No further data is therefore needed.

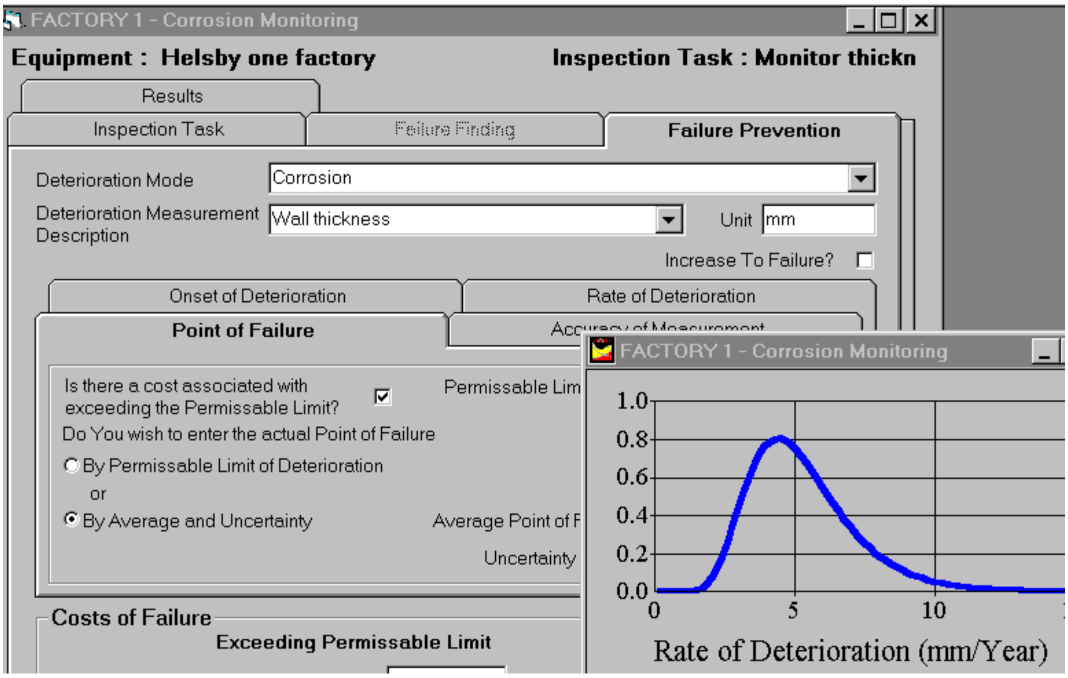


Calculated Results, showing optimal replacement point (12 years), the conflict between planned expenditure and risk exposures, and the cost/risk penalties for replacing too early or too late:

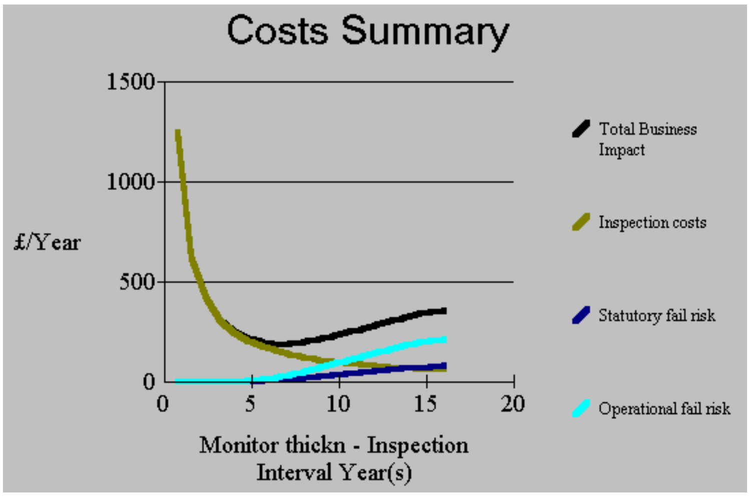


Appendix B: RISK-BASED INSPECTION CASE STUDY

A typical corrosion monitoring example - with uncertainty about the deterioration rate, the onset of deterioration, the point of potential failure and the measurement quality/accuracy. Inputs include the direct and indirect costs of monitoring and different levels of failure consequence. All data can be range-estimated and tested for sensitivity. Other examples range from visual inspections of substations, ultrasonic testing, vibration monitoring to operational checks of protection equipment and functional tests of standby equipment.



Results: showing optimal inspection interval at 6-7 years (current policy was 3-yearly, so a 50% reduction in monitoring costs is available). If regulator or safety requirements are limiting inspection intervals to, for example, 3-yearly, the following graph can be used to quantify the 'premium paid' for such compliance - and can help to justify alternative options (such as design changes, negotiations with the authorities etc).



Appendix C: PROGRAMMES of study

Systematic reviews of, for example, maintenance, inspection, projects or spares decisions introduce a problem of volume and time – how much effort is worth putting into consider each case individually, and how can 'templates' be safely used to represent families of similar circumstance with shared strategies. The MACRO experiences showed that 'batch' studies can use such templates with significant effect – up to 60% of the analytical effort can be avoided if the grouping of similar cases is performed correctly. This is also true of continuous review programmes – using criticality prioritisation criteria to select the level of review or analysis. For critical spares optimisation studies, MACRO has commissioned a dedicated 'batch' utility, whereby users can review and optimise large numbers of cases using tabular 'drag-and-drop' assumptions and large-scale block calculations of optimal inventory decisions.

In the case of condition monitoring and inspection optimisation, the opportunity goes even further – field experience has shown that the use of MACRO methods can be real-time and dynamic, with each inspection or condition report being used to update the assumptions and determine the next optimal time to inspect. This brings condition monitoring into the auditable world of fully risk-based, self-adaptive and business justified for all interventions.

For complex work programmes of different tasks being applied to different assets for different reasons, APT-SCHEDULE has pushed new boundaries in determining the best coordination, sharing of common resources and access opportunities (such as shutdowns). Only a few (c.6) major organisations have taken the MACRO methods this far to date, but they have invariably found massive scope for rationalising their programmes for total cost, risk and performance impact. A major manufacturing company, for example, has reduced annual downtime by 50%. National Grid has reduced critical circuit outages by 28%, and a large international oil company has extended shutdown intervals by a factor of 2:-