A review of overall models for maintenance management

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Abstract *Reviews overall models for maintenance management from the viewpoint of one who believes that improvements can be made by regarding maintenance as a "contributor to profits" rather than "a necessary evil". The reasons why maintenance is such a "Cinderella function" are largely historical and can mostly be overcome by new information technology (IT) and its falling cost. Progress is now being held up by outdated notions of what is economically possible in data acquisition and analysis, and failure to revise basic maintenance and reliability concepts, some of which are now 30 years out-of-date. Integrated IT permits mathematical optimisation of supra-departmental management decisions, e.g. co-planning of production with maintenance, overhaul/renewal of machinery and improvement of product performance/quality. Life-cycle profit (LCP) is a fair measure of overall effectiveness that emphasises the value rather than the cost of terotechnological activities.*

Introduction

Origins

This paper began as the overview chapter on management in a forthcoming book. However, it took on a life of its own as a justification for more detailed data collection and analysis and a case for improvement of currently standard models for the overall management of the maintenance function. The author feels that it is worth submitting these ideas to the scrutiny of other maintenance professionals outside the context of the book. In the draft book, several chapters on the mathematical theory of the reliability and availability of maintained systems, and models for optimising maintenance, inspection, renewal and overhaul schedules precede consideration of the overall management system requirements. So the reader would already understand something of the costs and benefits and the data needs of the models. Readers of the paper will either have to take these considerations on trust or else refer to books on reliability engineering (O'Connor 1989; Ascher and Feingold, 1984) and the extensive literature of maintenance modelling, of which four review papers are referenced at the end of the paper (Pierskalla and Voelker, 1976; Sherif and Smith, 1981; Valdez-Flores and Feldman, 1989; Dekker, 1995; 1996). However, be aware that many impractical models are praised by these reviewers, Dekker mostly excepted, and some useful ones ignored, seemingly for nothing more than a lack of originality in the mathematics.

Compatibility – data collection and feedback

The mathematical models cannot be applied without a system to collect detailed data concerning the operation, maintenance, failure, modification and costs of the machines and other equipment making up the plant. To choose the

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best optimisation model, every maintenance event must be fully documented, see Jardine (1973), Glasser (1969), Sherwin (1979; 1990; 1995), but much of the detail has other uses besides setting PM and inspection schedules. Whereas the application of such models does not ensure optimality, without them matters would almost certainly be worse. Any management model, therefore, that does not allow, or plays down the importance of data collection, analysis and feedback is not useful to those wishing to apply the mathematical models. Nor is it enough to pay mere lip service to these requirements; they must be properly considered. These conditions rule out RCM (which is fundamentally anti-data collection), and require that systems such as TPM, which contain some useful ideas, but are incomplete as models for total maintenance management, be suitably supplemented. This attitude to data and modelling is not universally agreed, but is justified within the paper.

What and who? Outsourcing

There has been a lot of discussion from a management theory (downsizing, core competencies, business process re-engineering, management by objectives, see for example Drucker (1968), hereafter referred to as simply MBO) viewpoint about outsourcing maintenance. It is for consideration that what maintenance is done, how often, how soon and how well, is more important than what agency, and that long-term cost rate or contribution to profit, over the life-cycle of the plant, should be the paramount criterion. It seems, prima facie, unlikely that all of a big manufacturing company's maintenance should, on the life-cycle cost/profit (LCC/P), criterion, be outsourced, nor that it should all be done in-house. The use of models allows the cost of the delays inherent in outsourcing to be factored in, whereas normal calculations may look only at the costs to the maintenance budget.

Equipment choice and replacement

Another major question in maintenance management is how far the maintenance manager's influence should extend into choosing what plant and supporting equipment to buy and when. A manager making these choices should be able to perform calculations, based upon data from previous machines and competing suppliers, leading to the realistic estimation of life-cycle costs and, with colleagues from sales, finance and production, life-cycle profits. The inclusion of such functions in the manager's job description makes him or her a plant engineering manager rather than just a maintenance manager. Again, it is not so important who performs these functions which influence and are influenced by, maintenance, provided that they are competent in the modelling techniques discussed above and use relevant, accurate data, together with sound engineering and commercial judgement, to reach rational calculated decisions in consultation with colleagues interested in the results, and, most importantly, with the OEMs. The main point is not that the plant engineer should lead the decision-making process, but that maintenance should be factored in. A principal argument in favour of detailed data and integrated IT is that accurate, unchallenged data are available to anyone with the skills to analyse and interpret them for the benefit of the company.

Historical perspective

Context and relevance

Management systems generally should be shaped to fit the nature of the work to be managed, and maintenance is no exception to this rule. Over the years, maintenance management has always developed somewhat behind the current requirement. To understand this, some history is needed. Aspects of the history of maintenance which are relevant to the main subject matter are briefly reviewed below, from what, for that reason, may at first be thought a somewhat personal, or even jaundiced, point of view.

Early days

Prior to the Industrial Revolution, generally held to have begun in England in about 1750, maintenance consisted of individual craftsmen such as carpenters, smiths, coopers, wheelwrights, masons, etc. repairing the buildings, primitive machines and vehicles of the day. As there was no concept of dimensional control or spare parts, failures were mostly repaired by making a new part to fit or repairing the old one. Moreover, repair rather than discard of assemblies was the order of the day, and the basic structures were either themselves repairable, or highly durable or both. It is also likely, in the absence of methods for calculating stresses, etc., that design evolution and repairs were closely integrated. The craftsman would naturally fit a stronger part to replace one that had clearly failed from being too weak, and would incorporate the design change in the next new machine.

Nelson's flagship, *HMS Victory*, the result of more than 300 years of slow design evolution, was 40 years old at the battle of Trafalgar in 1805, about average for the ships taking part on both sides. She remained in service or reserve until made obsolete by the development of steam power and iron hulls in 1860 (the Royal Navy was slow to join in the Industrial Revolution!), and afloat as a hulk until 1922, when she was dry-docked and restored. Over the years in service and preservation, almost all of her original structure has been replaced by new wood, some of it more than once. Such a maintenance policy was worthwhile because of the slow evolution and because even skilled labour was cheap relative to the utility value of assets. An idea of the asset value of *HMS Victory* can be gained from the fact that her timber came from the felling of trees 30-50 years old covering about 40 hectares. These trees required some specialised pruning and training when young to cause them to grow to the required shapes. About 60 men would have worked for over 6 years to build her hull.

Diagnosis and repair

Thomas Jefferson (1785) noted that musket parts were being made accurately enough to be interchangeable. The initially slow but accelerating development of this concept of spare parts which fitted without adjustment, accompanied by increasing complexity in the machines to be maintained, meant that the maintainer's job gradually came to require less craft skill and more diagnostic ability. Another factor in this change was quality control and then automation in manufacture, which made replacement of parts and later of whole assemblies easier, quicker and cheaper than repairs, particularly where craft fitting or other increasingly expensive skills were formerly needed.

Skills and training

Maintenance, however, continued to be performed by craftsmen, who originally learned as apprentices by watching and imitating their masters. As the actual job became more diagnostic, apprentice training was progressively centralised into craft schools, the "watch and learn" method having become inadequate for skill development in a reasonable time. Many companies in the UK found that operators and a new class of semi-skilled maintainers could do much, but significantly not all, of the work. Day-release schemes whereby apprentices were only available to do actual work for three days a week made them less attractive to managers, many of whom preferred to pay into the government-ordained training boards than to train apprentices themselves. The upshot is a mixed workforce which now needs more supervision than in the 1940s, and a craft skills and technician shortage, caused in part by this loss of training places, but also by the rapid expansion of tertiary education, which takes clever persons with skill potential out of the engineering orbit altogether (and gives them business degrees!). As a result, poor quality maintenance, particularly where craft skill is still required, became and remains a problem (see Sherwin and Lees, 1980). For example, there are now too few people who can align the bearings and seals with the shaft in a pump. As a result, the costs have shifted so that the reliability aspect of availability is now more important, relative to the maintainability, than it was in the past.

Shortages of competent repairers and their consequent higher wages have affected maintenance policy and subsequently the design of industrial, commercial, and especially domestic machinery. Toasters are now throwaway items in the USA, but are repaired in Kenya. White goods and motor cars for sale in rich countries are designed to require less maintenance, even though this may mean a somewhat shorter overall life than could be achieved otherwise for the same initial cost. The toasters that sell well in Kenya are simpler to repair and cheaper to buy than those in the USA, and fewer have thermostats or pop-up mechanisms. Similarly, in motor car manufacture, older, simpler designs are still in production in the third world.

Operational research (OR)

OR was defined by its originators as "the application of scientific method to operational problems". It was first applied to maintenance in the Second World War (see McClosky and Trefethen, 1954). An early UK study advised reducing the maintenance given to combat aircraft on the grounds that most of them would be destroyed before anything vital wore out. It took scientists from completely different fields to perceive that the wartime problem, to get them back in the air as quickly and as often as possible, was diametrically different from the peacetime task of sustaining readiness. Using scientific method, that is, inductive reasoning and calculations based upon real-life data, they worked out which maintenance should be dropped and which routines could be done at what increased intervals. This and most of the other wartime OR work was sharp and to the point. Afterwards, academic OR unfortunately became more a branch of mathematics, and the requirement for rigorous analysis of the problem prior to modelling it, which the early OR scientists all emphasised, became subordinate to the development of increasingly complex techniques. Early failure following repair or PM was often mis-interpreted by the industrial statisticians and operational researchers, as well as by some engineers (who really should have known better), as "over-maintenance" when it was really just poor workmanship or faulty spare parts. Other researchers disagree, but this author believes that the nett effect on maintenance practice of these statisticians and OR people was probably negative because they too often failed to analyse the problems properly, being more concerned with figures than facts, and lacking engineering knowledge and experience. The engineers could not square what the operational researchers were saying with their observations of reality, which led to most regrettable mutual distrust, in a situation where co-operation can be very fruitful.

There was a revival of interest in maintenance optimisation among non-engineers in the 1980s, which evinced no measurable response from the engineering world, for three reasons:

(1) *Applicability*: the papers were mostly very theoretical, used difficult mathematics, would have been impractical to apply and required data that were not then generally available.

(2) *Accessibility*: they were published in journals of applied mathematics and OR, which most maintenance engineers do not read and few would understand if they did.

(3) *Motivational*: many of the models were exercises in advanced mathematics written because of the publish-or-perish academic imperative, rather than proper OR.

True OR analyses the problem first and bases the model upon the realities found. Above all, it does not treat quantities, such as system rate of occurrence of failures, (ROCOF), which vary with the maintenance policy, as intrinsic invariant parameters of the optimisation problem. The principal type of misunderstanding is the general one of the bathtub curves, about which enough has been said already elsewhere (see Ascher and Feingold, 1984; Sherwin, 1997). The prevalence of these unusable models has, arguably, prejudiced the maintenance engineering profession against optimisation in general, and pushed it towards softer and less sound methods such as RCM (see Sherwin, 2000).

It is even more unfortunate that the management consultants have espoused the maintenance fads, particularly RCM, with the same over-hasty and uncritical enthusiasm with which they embraced the general management fads (MBO). Management consultancy firms have been in a position, through their advice, to effect integration of companies' principal internal functions, but integration of the maintenance function cannot be accomplished under the fads, and so an opportunity has been lost for at least a generation of IT systems.

Supervision and computers

It was unfortunate that the first period (1960-1975) of rapidly-expanding interest from non-engineers and engineers with statistical knowledge, coincided with the need for more supervision, and that this also happened when the supervisors were driven indoors by increasing paperwork demands stemming from the need to feed data into the computers which reported monthly summary statistics and trends to higher managements of low and falling engineering knowledge. The supervisors should have spent more time walking round advising the technicians and fitters and inspecting their work. The period when the computer was their master has now passed in most companies, but it is not yet the slave it should be, and they are often now plagued by managerial de-layering, so that nobody in authority and with competence has the time to think clearly and critically about basic questions of maintenance policy. The consultants they send for then often make things worse in the long term, by advising actions that produce only short-term savings.

Manuals and (re-)training

Returning to the beginnings, the rate of advance of technology eventually became too rapid for a skilled technician to complete a working life of around 40 years without retraining. This has led to the requirement for maintenance manuals for machines, with diagrams on how to remove and replace parts, part numbers for re-ordering spares, diagnostic charts with solutions for every conceivable set of symptoms (except the present set!) and suggested schedules of PM.

During the introduction of CNC machines in UK factories in the 1970s, much down time was generated by the ignorance of the electricians who had never been trained in solid-state electronics or machine-code programming, but who were expected to deal with the teething and running problems of the new systems. Matters became so bad that the electrical trade union ran courses for them because no one else acknowledged the problem. There were many other, less stark, examples of new technology being brought into service without adequate training of the maintainers, but the problem is now better understood. However, there remain crucial three-way choices in each case, between training a specialist who then becomes obsolete at the same time as the equipment, giving a short course to a technician with pre-existing but expensive general skills and theoretical knowledge, and outsourcing. To make these choices rationally, data and consistent methods for its analysis are needed; adherence to faddish prejudices is simply not competitive any longer.

Scheduling, planning and computers

It soon became necessary to find a better way to bring to mind the times to do maintenance as laid down in the manuals. This led to companies adopting various schemes for planning maintenance within the resources available. Co-planning of maintenance with production is still rare, although the computer has made the necessary rapid re-planning possible as production requirements adjust to market demands. The fighting services use schedules because their (peacetime) problem is not so much to keep machinery working as to have it in a high state of preparedness for war. This involves a nice balance between use for training the operators and maintenance. A disciplined approach to priorities for PM was therefore needed. Most of the early computerised maintenance bring-up-and-record software, e.g. COMAC™, was based upon the Royal Navy's PMS1 (Planned Maintenance System #1). PMS1 was originally conceived in about 1950; it used cards in a filing drawer for the bringing up and recording of PM, and loose-leaf Kalamazoo™ files for recording the history of failures, modifications, clearances and performance measurements. The front of each PM card recorded when the routine had last been done, and its position in the filing drawer gave the week or month in which it was due to be done again. On the back were instructions telling the technician what exactly was to be done, including, in later versions, what tools and spares he would need and which pages of the manual and which drawings were relevant. There were also forms to send off if the ship's engineers felt that the frequency of the maintenance routine should be changed or the machine or its environment modified to obviate repetitive problems. These were considered by a central fleet authority together with solicited and unsolicited reports from other ships with the same and competing equipment. However, all decisions regarding PM frequency were made on engineering judgement and Pareto analysis; none was calculated and the data relating to failures and PM achievement were not analysed for distribution. No attempt was made initially to plan the PM around the ship's operational schedule, the cards were planned into the appropriate week and done as soon as possible thereafter. The objective was high material and training readiness; life-cycle costs were secondary. This attitude persists in RCM.

Reliability engineering

Reliability engineering started on the German side in the Second World War, in connection with the flying bombs and early ballistic rocket weapons, V1 and V2. The absence of a pilot to make adjustments changed the situation from one of skill to one of probabilities. Maintained systems were not considered because these weapons did not come back. The subject is still dominated by reliability rather than maintainability and availability, and more diligently applied in military than in civilian circles. Reliability specialists are either applied statisticians or engineers with statistical knowledge. Those interested in maintained systems are still a minority, but have contributed more to terotechnology than the OR people, and the contributions of systems and logistics engineers such as Blanchard, have been crucial (Blanchard and Lowery, 1969; Blanchard, 1986). Specialists tend not to communicate across subject boundaries as much as is needful. Most real systems are maintained, but the persistent confusion between the bathtub curves for systems and parts has delayed progress.

Maintenance and safety
Periodic maintenance was first prescribed to improve safety rather than to increase availability or reduce costs. Examples are the examination and pressure testing of boilers and re-setting of safety valves. Many of these measures include statutory intervals. This restricts the scope for optimisation. More recent legislation, for example the Norwegian government regulations for the design and operation of offshore oil platforms, require the risks to be assessed and the analysis and calculations approved in an independent audit by a licensed organisation.

Environmental protection
The latest additional objective for maintenance is to promote environmental sustainability. There are three principal strands. First, maintenance holds noxious emissions to designed levels, which may be the subject of legislation and regulation. In this case, the standards are usually absolute even though the procedures may also require approval, partly to protect maintainers. Second, making things last longer reduces energy, resources and emissions. Third, maintenance and disposal experience can be fed back so designers can make their next designs more environment-friendly. All three aspects are of increasing global importance. Modern maintenance management systems now generally include provision for safety and environmental legal requirements and the best such systems provide incentives for doing better.

Costs and benefits
The language of higher management is money, and so the costs and values of maintenance to the company should be expressed in cash terms as part of the system of management. Most accountants still regard maintenance as a necessary evil that costs what it costs. A survey published as long ago as 1970 by the then Ministry of Technology in the UK showed that over £3 billion annually was being spent by manufacturing industry, of which at least 8-10 per cent could be saved by some very basic improvements, such as prevention of rust by more effective painting.

Since about 1985, when advanced companies finished installing TQM and started looking for other improvements to LCC, there has been more interest in reducing maintenance (and other) costs, but not so much in optimising the expenditure for the benefit of the company. Downsizing the company reduces all classes of cost, but probably not in proportion to turnover. This report, (Ministry of Technology, 1970) started the terotechnology/LCC/P movement which has advanced at slow but varying rates in different countries and industries world wide, but has as yet (2000) not made a really significant impact upon entrenched attitudes.

Performance measurement
It has lately become fashionable again to measure the performance of maintenance (and all the other) departments by means of dimensionless ratios

such as (maintenance) cost over sales, or profit. This actually has quite a long history (Priel, 1974). It was popularised as part of terotechnology, but has recently been revived in support of MBO. The problem with measuring maintenance performance is that the effects of actions taken (or not!) today will reverberate for a long period into the future. It is easy to save money today only to suffer much more expense later. Some writers, notably Dwight (1998), have tried to take this delayed impact effect into account, but most do not even acknowledge that it exists. The author's view is that such overall comparisons can too easily be doctored by ambitious managers, and in any case distract attention from the need to gather data at the component level, analyse it and optimise the schedules. A more cynical view would be that they are an attempt to justify data collection for management summaries only, giving the higher management sticks with which to beat their juniors, omitting to retain, for the use of those juniors, the information needed to work out how to make things better. Optimisation, ultimately of system LCC/P, but starting with PM to fallible components and building upwards does consider future as well as present costs, by its very nature. It is more important to improve maintenance performance than to attempt to measure it by dubiously relevant metrics, but if it must be measured then it should be done in the same way as other functions, i.e. we should calculate how much the maintenance function contributes to life-cycle profits (LCP). Mindless economy drives often cut the benefits of maintenance actions as well as the costs. If the benefits exceed the costs, as they surely should, then clearly the proposed cut is uneconomic. In the allocation of the benefits, improvements in quality of product and output of plant stemming from PM optimisation tend to be claimed by production, and the increase in market share is ascribed to marketing. The problem is that these other departments often have contributed as well, and the data system is unable to make fair apportionment even if the contribution of maintenance is unusually acknowledged.

It is also vital that the IT system can produce the evidence to show whether increases or cuts to the maintenance budget would be justified by the current situation. It is by no means certain that maintenance should be cut because sales have been lost. The result is just as likely to be further lost sales due to bad quality or failure to deliver. It is important that existing machinery is kept in good condition until it can be replaced. However, this is impossible to prove without improvements to the data system.

Banks prefer not to lend to companies whilst they are losing money, and the only way back to prosperity may be to make better product with old machinery and so increase one's share of a cyclically diminished market. Downsizing is not the answer; even if the product is obsolete, it is usually better to find another one that can be made on the same machines. Returning to core competencies eventually implies making unwanted products. The sale of the machinery will not even pay the redundancy money for employees who may well be sorely missed when times improve. It is often the experienced workers who leave.

Conclusion

Systems for maintenance management should be viewed against this historical background. The reasons why maintenance is organised as it is are in many cases historical rather than logical, but reform must nonetheless take the history into consideration because it shaped the current conditions, including the abilities and attitudes of the people involved. Ideally, such systems should include provision for the improvement of LCC/P through the adjustment of schedules and the modification and replacement of equipment, which requires full integration of maintenance with the other major company functions. Some systems cannot do some of these things, and most cannot do them all, numerately and scientifically.

Discussion of other historical viewpoints

An alternative view of recent maintenance history and a more thorough review of maintenance management literature than would be appropriate here was compiled by Kelly (1989), see particularly Chapter 3. Pintelon *et al.* (1997) view the history as a progression from a production task and a "necessary evil" in 1940-1950, to special maintenance departments, "technical specialisation" in 1960-1970, to efforts at integration, "profit contributor" (1980-1990), with external and internal partnerships' "positive co-operation" as the latest trend. This is fairly accurate for the English-speaking countries, Western Europe, Scandinavia and possibly elsewhere in respect of the prevalence of the ideas in academic circles and local experiments, but general practice is about ten years behind. It also depends upon how loosely "integration" is defined. Books on computer-integrated manufacture have no place for maintenance on the organisation charts. It is also questionable whether outsourcing has, in practice if not in theory, become another fad; it is perhaps too early to tell. The savings in integration often and mostly come from minimising downtime and doing work in system free time, which becomes more difficult under outsourcing.

A recent survey of over 400 Swedish companies (Jonsson, 1997; 1998) by a doctoral student supervised by the author, indicates statistically that companies which have installed advanced manufacturing technology (AMT) without integrating their information and managerial control systems, particularly in respect of maintenance, have fared less well than those which have made even perfunctory moves towards integration. Case studies (Jonsson and Lesshammar, 1999) indicate that there may be a cyclic element operating, by which good practice in TQM and maintenance leads to better market share, so that machine utilisation increases to the point where maintenance is neglected or becomes inadequate, quality falls, market share is lost and so on. The author observed something suspiciously like this in the UK motor industry in the 1980s, following the introduction of a new design, but failed to start to document it until too late to distinguish unequivocally between defects caused by under-maintained or over-stressed or out-dated machinery and those due to hurried faulty assembly of the product.

Overall maintenance management models

Introduction

In this section we describe a limited selection of schemes for the organisation of maintenance, and compare them with each other and against the needs of a system that leads towards optimisation. The wording "leads towards" was carefully selected to indicate that we appreciate that absolute and lasting optimisation of the maintenance of any working system is not possible; the optimum is never achieved because it is a moving target and because the data for its estimation are never quite complete or up-to-date, and seldom sufficient in number. However, we believe that active pursuit will keep us nearer the moving target than passive adherence to OEM's advice or first calculations, and that the expenses of the chase, including adequate data collection, are worthwhile, particularly on an LCP basis, and perhaps over several generations of plant.

Basic terotechnology model

This is taken from the original UK government work and is contextually significant because, borrowing from the quality gurus, it called for feedback of information at several points in the maintained system's life cycle.

However, all the feedback goes to the designers, and so, from the diagram, one does not immediately appreciate that any actual changes, to either the design or the maintenance policy, are contemplated between successive generations of machinery. Figure 1 shows the basic idea, expands upon the data collection, analysis and schedule optimisation etc. that should occur during the operation phase, and emphasises the needs for FMECA and testing of new designs and training operators and maintainers. It should be understood though, that the originators of terotechnology, led by Dennis Parkes (Parkes, 1970), did not specifically mention optimisation as such, but did advise the revision of schedules as a result of experience. The author's experience is that the position of the optimum and the sensitivity of cost rate to PM interval are very difficult to judge without calculation. A model of the product design cycle appears in British Standard 5760 Pt 1, which is on reliability programme management. This omits costs but includes all the reliability engineering management and feedback loops necessary and desirable also in the development of machinery for manufacturing. One firm's product is often part of its customer's manufacturing plant.

Advanced terotechnological model – need for integrated IT system

The development in terotechnology from LCC-based to LCP-based may seem minor, but is in fact profound because it allows the maintenance function to be seen as contributing to profits rather than just spending money. To accommodate the profit aspect it becomes necessary to acknowledge dependencies and connections that were always there but were not previously specifically brought into policy calculations and company planning. Examples are the effects of maintenance on product quality and prompt delivery, which in turn affect market share, overall profit margins, pricing and the ability to renew plant sooner with the latest most cost-efficient machinery, and so consolidate commercial advantage.

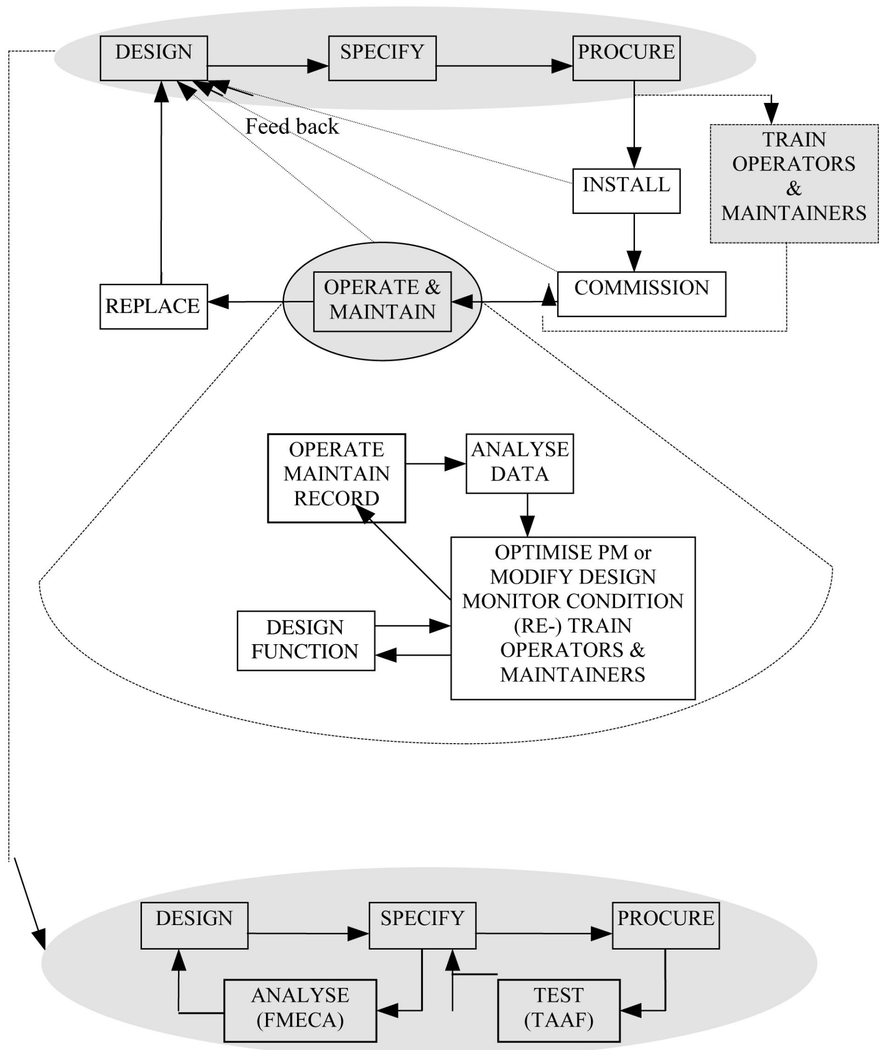

Figure 1.
Terotechnology – basic concept with advanced additions

LCP will remain just a worthy objective unless the company's IT system is sufficiently integrated to cope with the demands for instant, detailed and unambiguous information with which to feed the mathematical models and other decision-guiding procedures, predictions, simulations and calculations. Conversely, an integrated IT system obviously has its own waste-cutting advantages if it can be made good enough for everyone to want to use it; but for that to occur it must be based upon an agreed overall model of the way the factors of production and management interact. Possibly, TQM/terotechnology/LCP is the best available. By contrast, a conventional IT system is designed to support the MBO-based theories of management, which are about control and the elimination of supposedly inappropriate functions and enterprises, whereas in a TQM/terotechnology/LCP-supporting IT system, the keywords are co-operation, information exchange and growth.

This circularity prompts the comment that, increasingly, the IT system will determine the way the company is managed, so a decision about management style is required before specifying the IT system. Computerisation is introduced to save time, then, increasingly, the time saved is translated into staff reductions, so that remaining staff are forced to use the IT system and therefore to espouse its underlying managerial theory. There would prima facie seem to be a sounder long-term basis for a management system based on co-operation, and TQM/terotechnology/LCP, than on internal competition between managers, MBO, this year's bottom line and core competencies.

The preferred seamless combination TQM/terotechnology/LCP is of course a total management philosophy that transcends maintenance, but is obviously incompatible with MBO. Which of its overlapping constituents is regarded as part of which of the others is relatively unimportant compared with the overall concept of complete integration, which means sharing and inter-connection in the IT system and full consultation and co-operation among the managers. However, within it, a system for maintenance management, conducted mainly through a module of the IT system, is necessary, and it should connect with the other modules through data-sharing and feedback links.

The Eindhoven University of Technology (EUT) model

This model is the brainchild of Prof. W.M.J. (Bill) Geraerds and his Dutch colleagues, notably Gits and Coetzee (1997). He has has pointed out that the EUT model originally set out to fill a gap left by the terotechnology models, although it is arguable whether, as he puts it, these "tended to widen the scope of the maintenance practitioner so much that they totally neglected the processes inside the maintenance organisation itself". It seems more likely that the early advocates of terotechnology merely wanted to emphasise the broader aspects, and did not so much neglect the existing internal ones as take them for granted. Even so, this was perhaps unwise in the present context, because it amounted to neglect to sharpen the incisive tools that could have made the dreams of the terotechnologists come true. That is, it was necessary, not only to broaden the scope, but to do the traditional things, particularly maintenance scheduling, more scientifically. In order to do scheduling better, it is necessary to collect and analyse data and then to use appropriate OR models to optimise for maintenance type and intervals. The latest paper on the EUT model is that by Geraerds himself to the 1997 conference of the International Foundation for Research in Maintenance (IFRIM) which presumably represents the fully-matured Eindhoven philosophy.

The model describes the sub-functions of the function known as maintenance and their mutual links. The model postulates a maintenance department (MD) which makes use of contractors and OEM support. A systems (or industrial) engineering view is taken; maintenance is regarded as a set of inter-related processes, with its output affected by planning and control. Feedback to design is included, but not the (re-)design process itself. Within the model, 14 sub-functions are recognised as making up the maintenance management function, as described in Table I and arranged in Figure 2.

Although Geraerds is not himself wholly convinced of the value of optimisation models as they are generally presented, and certainly not in isolation from a system of management, there is no doubt that the EUT model does provide a sound basis for a fully integrated maintenance system, with OR models where appropriate, leading to a total system that diligently and continuously pursues optimality as closely as possible. The EUT model does not call for an integrated IT system, but it does not preclude it.

Sub-function	Major activities and decisions
Technical systems (TS) which are to be maintained, many and diverse	Asset register, configuration control, integration of maintenance across TSs
Internal resources, including manpower, available for the function	Degree of centralisation, contract-out decisions, skill training, operator involvement, work study
External resources available from contractors	Special skills and equipment, demand peaks, cost in recession, liability and responsibility
External resources available from OEMs	Undesirability of over-dependence on OEM, LCCs, symbiotic feedback
Maintenance planning and control (MP&C)	Bring-up and record PM, integration of PM with repairs, supervision of workmanship, overhauls & shutdowns, critical path analysis/PERT
Inventory control of consumables and non-repairable parts	Logistics, slow-moving spares, cost of waiting time
MP&C of rotables (machines and assemblies replaced as a whole and repaired at leisure, made possible by holding complete spare assemblies – includes echelon repair)	What should be rotable? Spares and new units, modification states, module boundaries, in-house or contract (for a mathematical model, see Sherwin, 1996)
Evaluation of results (inevitably involving data collection and analysis)	Changes to schedules, methods, organisation, maintenance policy, operation
Terotechnological feedback	Mainly a task for OEMs to improve the next generation of TSs
Design methodology for a TS	Checklists, FMECA
Specification of a TS	Selection of new machines, avoiding old problems, LCC/P
Actual design of a TS	If OEMs do not provide data, must look at drawings, ask other users
Manufacture of a TS	Maintenance may influence QC
Design of the maintenance concept for a TS ("concept" equates roughly with PM schedule + repair policy)	Determines resources, not fixed for all time, changes with modifications, stresses and intensity of use, and as data accumulates

Table I.
Eindhoven University of Technology model

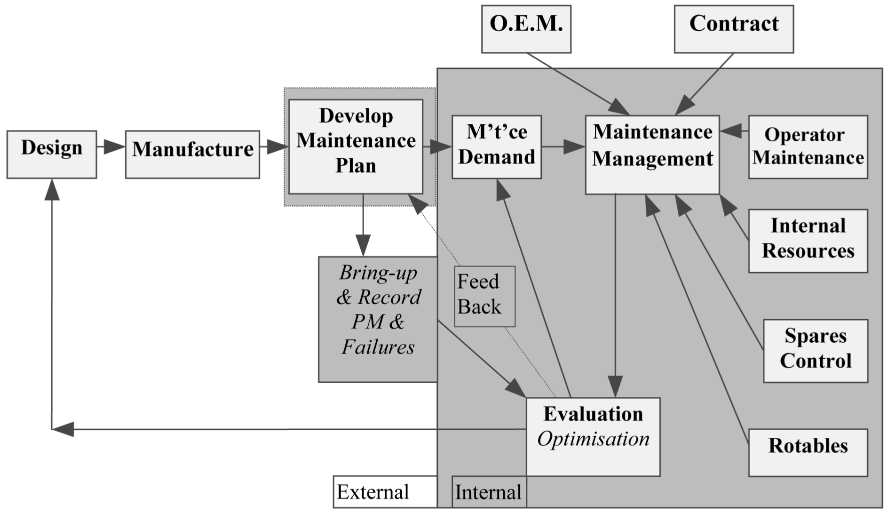

Figure 2.
EUT model for a TS with suggested additions in italics

The terotechnological model with which Coetzee compares the EUT model is less advanced than the one proposed in the previous section, i.e. it lacks all the italicised and expanded portions of Figure 1. We would also make maintenance plan development an internal rather than an external sub-function, and have it subject to change as part of evaluation. This is because experience suggests that the same equipment may need different maintenance regimes in different circumstances, and that external agencies such as the OEMs may not be aware of these circumstances or competent to assess their significance. Users should, in our view, be responsible for their own data analysis, optimisation and review of schedules. This is emphatically not to say that OEMs should not be involved at all, nor that companies should not employ consultants to cover gaps in theoretical knowledge, but they should choose carefully, watch what they do, correct their misapprehensions and learn valid techniques.

The EUT model is clearly one from which we can learn a lot, but it does not cover everything, and did not set out to do so.

Total quality maintenance (TQMain)

This model was developed by Dr Basim Al-Najjar, as part of his PhD dissertation, which the author supervised (see Al-Najjar, 1996). It continues the line of development started by Prof. Hans Ahlmann at Lund University in Sweden, another complementary branch of which includes the development from LCC to LCP. It is soundly based on the Deming cycle (plan-do-check-act-plan, etc.), which is the foundation of TQM, and can be used for the improvement of any technical or managerial system. See Figure 3 for a schematic representation of TQMain. Al-Najjar's research focus is on condition monitoring (CM) by vibration analysis, and it is therefore natural that his managerial model for maintenance should specifically include inspection and monitoring maintenance policies in its structure.

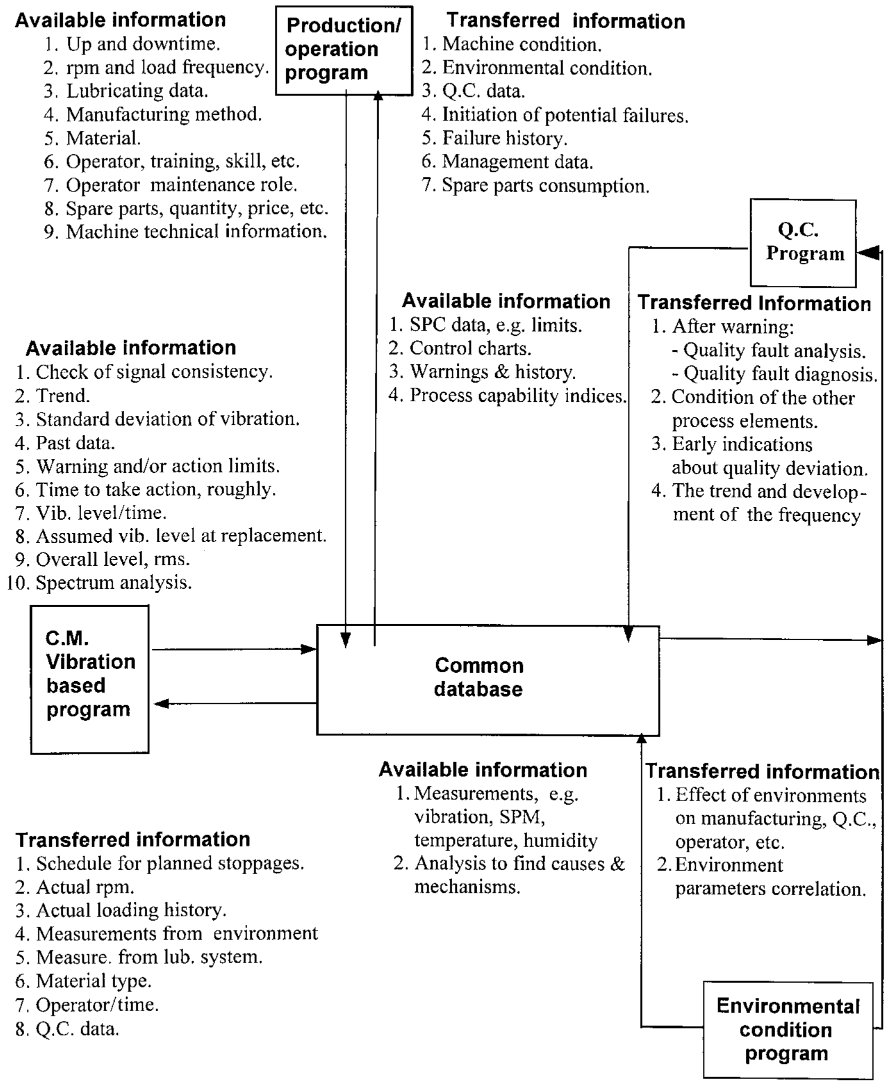

Figure 3.
TQMain schematic

He starts by reviewing the increasing cost of maintenance, pointing to evidence that it has recently been going up faster than inflation and increasing as a proportion of company costs. In these circumstances, it becomes desirable to use as much of the life of each wearing part as possible, to maximise availability and minimise production and quality losses due to stoppages, rather than basing policy on the failure time distributions (age renewal) (Glasser, 1969; Jardine, 1973). As the cost of monitoring has been decreasing relatively during this period of increasing maintenance costs, he argues, in the author's view correctly, that more maintenance should in future be done "on-condition".

Another principal strand of TQMain is that maintenance should be integrated with production and scheduled with it. This argument is also compelling. It involves two-way traffic. The preventive maintenance, whether age or on-condition, should be scheduled to avoid busy production periods, but on the other hand, production schedules should incorporate time for the maintenance calculated to be essential to sustain quality and minimise total down time. It is recognised in TQMain that integration of maintenance and production schedules will require an integrated data system based upon the Deming P-D-C-A cycle, and sufficiently discriminatory to choose and optimise a policy for maintenance. It does not prescribe how exactly this should be achieved.

Success in TQMain is measured by a modified version of the overall equipment effectiveness (OEE) measure of TPM, which he calls overall process effectiveness (OPE). The OEE measure combines the six big losses of TPM under three headings: availability (including preventive down time), speed (actual production rate/theoretical production rate) and quality (l – proportion defective):

$$\mathrm{OEE} = A.\eta.(1 - p_d) \quad (1)$$

Thus effectiveness can be calculated as the ratio of the actual unit cost to the unit cost that would apply with OPE = 1 and no set-up cost, i.e. CE = C_a/nc_o.

TQMain expands this measure to show how its constituent factors are calculated, but it also calculates over a whole process rather than a single machine, and recognises that the same machinery may have different OPEs for the different processes it may be tasked to perform. The OPE measure therefore relates to the machinery system's capability to make the product or provide the service rather than just the properties of individual machines. By expanding to show how A, η, p_d are formed, these factors can be related to the maintenance policy, upon which they are then seen to depend. Thus any two policies for which data have been collected (or estimated) can be compared by a second measure of cost-effectiveness (CE):

$$\mathrm{OPE} = \{1 - N_s/\mu T\} \cdot \{1 - (n_m/\mu_m + t_r)/t_o\} \cdot \{1 - (n_f + n_c + n_s)/n\} \quad (2)$$

i.e. OPE = {1 – no. of stoppages/repair rate · loading time} · {1 – (no. of minor stoppages/minor repair rate + time lost to reduced speed operation)/operating time} · {1 – (defectives made just after stoppages + defectives made when process was in control + defectives due to assignable QC causes)/total no. made}. Then:

$$\Delta\mathrm{CE} = 1 - C_a/C_b \quad (3)$$

where ΔCE is the improvement in cost-effectiveness measured in terms of the total costs for a batch of the same size (n), before (b) and after (a) a change in policy. The absolute cost-effectiveness can be calculated as the ratio of the actual unit cost to the unit cost that would apply with OPE = 1 and no set-up cost, i.e. CE = C_a/nc_o.

It would perhaps be better if set-up time were included in the calculation of OPE, and its cost in CE. The omission makes it difficult to compare JIT fairly with other production flow management schemes. However, this is a better basis of comparison than the original TPM "six big losses" because it brings out the part played by maintenance more clearly.

TQMain also recognises that the relative importance of the various factors to be considered in maintenance policy-making varies between projects and with the viewpoint of the manager. To illustrate this, Al-Najjar devised Figure 4.

Kelly's philosophy

Dr A. (Tony) Kelly has been researching and consulting in maintenance for many years and has written several books including a standard introductory work with John Harris on the management of the maintenance function (Kelly and Harris, 1978; Kelly 1984; 1989). It would be impossible and inappropriate here to try to even summarise this large body of work and the development of his ideas over the years as a result of continuing experience. However we may pick out some themes which chime with that of this paper.

Kelly regards maintenance as the control of reliability, a thought with which we heartily agree. He frequently draws figures showing inputs being converted to outputs through a system of maintenance, and is strong on the analogy with

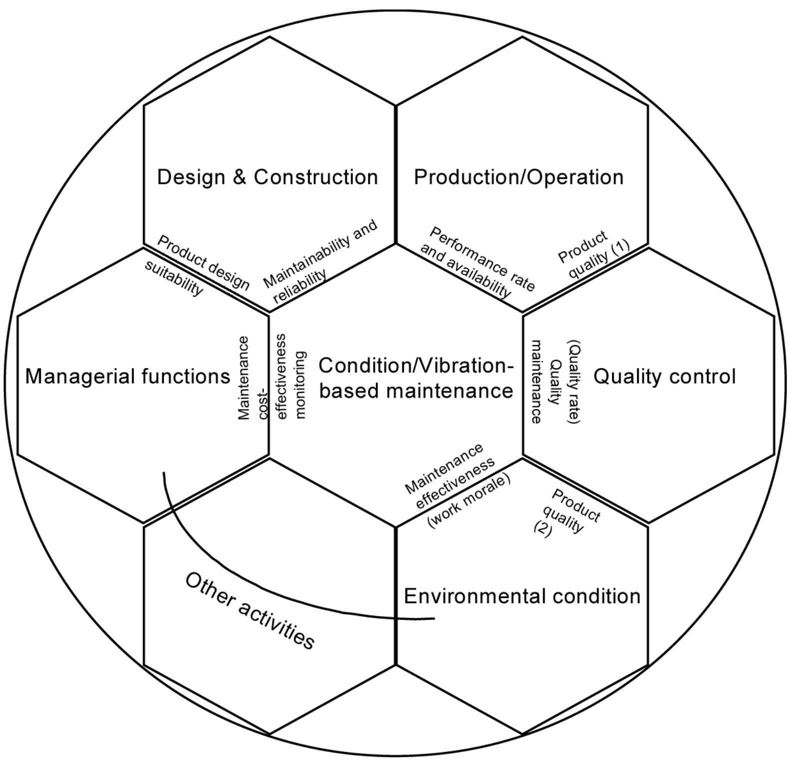

Figure 4.
The TQMain football

the physical control of engineering systems. Rather than just describing the steady state result, Kelly tells us how to set up a maintenance system. His general approach is fairly conventional management science, being developed from the following ten-point plan:

(1) definition of the function of the maintenance system in terms of
(2) objectives; which lead to
(3) strategy; which is identified by
(4) forecasting the way the plant is to be used; from which is derived
(5) the maintenance workload; which in turn dictates
(6) the structure of resources, including manpower; then
(7) the work-planning and work-control system is built around the resources.
(8) All these factors influence the administrative or decision-making system; and
(9) maintenance control ensures that the system works towards the objectives.
(10) A documentation system, either on paper or computerised, is needed and is regarded as central to the operation of the entire management system.

Kelly recognises all the major maintenance policies and ranks them as follows:

(1) design out if economically possible;
(2) condition-based (condition judged with machine running);
(3) condition-based (condition determined by inspection while stopped);
(4) age/block preventive maintenance, which he calls "fixed time"; and
(5) operate to failure.

Kelly's ideas are a mixture of elements which could have come from TPM, terotechnology and RCM, except that his principal analytic work pre-dated all of the above and was to varying extents influential to their development. He has also clearly been influenced by ideas to be found in Deming and Juran's work on quality, and was well aware, possibly before others, of the less obvious connections between quality and maintenance.

However, like most writers on general maintenance management, his views and methods for optimisation of schedules are sketchy, even in his latest book. He acknowledges the value of data, but does not insist upon it being as detailed as we would like. His mathematical models are generally over-simplified. Examples are the misinterpretation of the gearbox data from first and subsequent failures and his famous example of the wear-plate in a wood-chipping machine. The former case is detailed in a book published by the Institution of Mechanical Engineers no less (Kelly, 1988). In it, times to first failure from new of automatic bus gearboxes are Weibull-analysed as $\beta = 2.25$ and subsequent failures as $\beta = 1.1$ with halved mean. The failure pattern of the re-conditioned boxes was mis-interpreted as truly Poisson when in fact it was almost certainly due to mixed ages of parts. Weibull analysis is only valid for parts or for assemblies up to the first failure. This is explained in great detail by Ascher and Feingold (1984) but can be summarised by considering how, when machines fail, we renew parts, not whole machines. Weibull analysis of repetitive failures is only valid if the repairs are renewals (or restorations to good-as-new) at the level of the analysis, which renewals of only the part(s) that fail clearly are not. For the wood-chipper, he assumes no failures before a minimum of 12 months and changes the plate then, without checking whether allowing some failures by extending the interval would be cheaper. This is reminiscent of the even more simplistic approach of RCM, which Kelly seems to regard as an acceptable policy. Writers on maintenance optimisation, conversely are a bit sketchy on maintenance management. Each to his own, but it is becoming increasingly necessary to incorporate optimisation into the system of management, through development of the company-wide IT system.

Total productive maintenance (TPM)

TPM (Nakajima, 1988) is assumed to be familiar to readers. It attempts to cover the major problem posed by just-in-time manufacturing (JIT), which is that you cannot plan maintenance of productive machinery which involves dismantling, when the next KANBAN (token to order the immediate production of some more parts) could arrive at any moment. It relies upon the fact that the deterioration of machines is accelerated by abusive operation and lack of primary care, such as greasing, spannering and cleaning, all of which can be alleviated by the operator. The problems come later, the efforts of the operator can postpone the need for PM, but unnecessary, costly failures will still occur if it is never done. TPM does not exclude PM – in fact it is advocated in Nakajima's book (1988) – but there is no specific strategy to allow it to be planned, and so it is almost bound to be neglected if the factory gets too busy, which is just when it is most needed. The dramatic falls in failure rates come from increased operator care, especially the operator acting as condition monitor, which reduce the frequency and duration of periods of enforced down time. They do not occur in plants which already have sophisticated PM and CM, although a small return can be expected from operator training and the "parlour factory" concept. Better data analysis and optimisation could take advantage of the reduced part hazard rates due to increased operator care, but this aspect is not stressed in TPM texts.

The calculation of so-called overall equipment effectiveness (OEE) in TPM as the product of availability, quality performance and speed, is not really a complete analysis. It does not take account of costs and profits, and so is not a complete measure by which competitive machines or systems should be compared, or the deterioration of systems over time should be monitored. OEE is only a part of the LCC/P equation. Within those limitations though the OEE concept is useful, particularly if expanded a little as in TQMain, described previously.

The "six big losses" are not in fact mainly concerned with maintenance performance. They are mostly production losses, in which maintenance policy is one effect among several. They form a useful analysis of part of the problem only. They do not all relate directly to maintenance, and it is not made explicit that they all have indirect connections with maintenance. Again, this is done a little better in TQMain, where the connections between maintenance, speed and quality are made more explicit.

It is a part of TPM to have small group activities devoted to devising and implementing improvements in areas suggested by shop-floor workers as well as management. A full TPM implementation programme looks very much like a TQM or quality improvement programme (QIP) with, naturally, an emphasis on maintenance. It certainly works better if there is a pre-existing TQM aegis, and may not work at all well if there is not. It would probably be better if the TPM programme, as advised by Nakajima, were altered to follow the order of a QIP more closely. No form of workers' small group activities works well in the absence of the total management commitment associated with TQM. There would seem to be no need to duplicate the quality circles which are a part of fully developed TQM; inasmuch as maintenance affects quality, it will probably be better that the quality circles deal also with shop-floor maintenance improvement problems. In fact, many QC suggestions are already for better maintenance practices or the (re-)introduction of routine maintenance. In other cases, the operators are likely to recognise that a machine needs to be replaced or extensively overhauled long before the management wakes up to it. The initial project groups and workers' groups advocated by TPM do not mix senior and junior personnel as the RCM groups do. The first are senior groups concerned with finding the causes of low OEE through analysis of problem mechanisms, and the second are shop-floor groups who suggest minor adjustments to PM frequency, work content and methodology. Both are essential to success.

Unlike RCM, TPM contains nothing that is actually wrong or detrimental to company economics, but it is incomplete as a system for maintenance, and as a philosophy for terotechnology. However it does try to show how maintenance interacts with other functions and, importantly, includes a means of measuring its own success. It is unwise to apply it without first installing a full TQM system, which in Japan would be taken for granted. To be fair, Nakajima states specifically that TPM is concerned only with equipment aspects of terotechnology. He regards TPM as part of terotechnology, which in turn is a part of logistics (see Figure 5). However, the consultancy firms pushing TPM have tended to present it as a complete answer to the maintenance management task.

Reliability-centred maintenance (RCM)

The author has recently written a critique of RCM (Sherwin, 2000). Suffice it to say here that RCM is based upon an erroneous analysis of data collected for a report that appeared as long ago as 1960. RCM purports to be a procedure for discovering what maintenance is required by an asset in its operating context, in particular what must be done to ensure that it continues to provide its

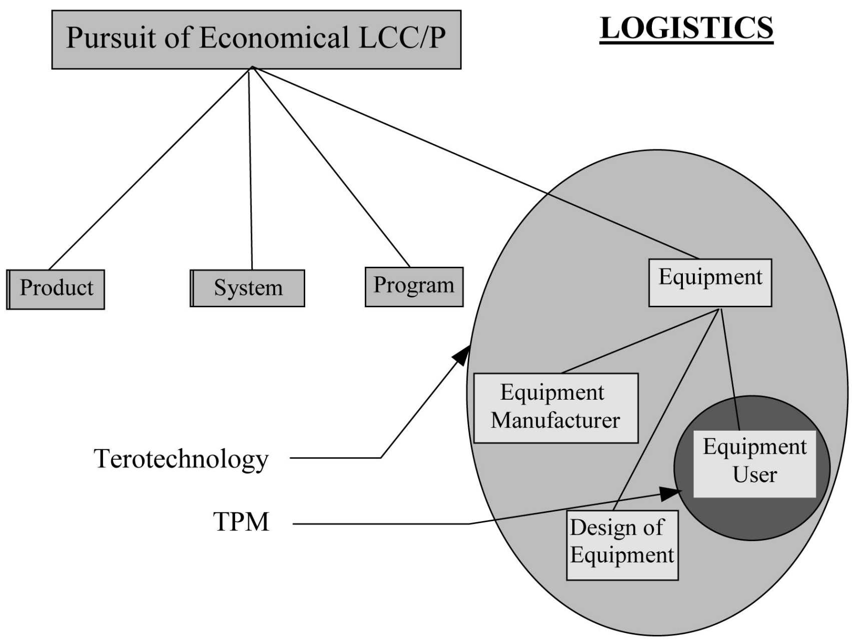

Figure 5. Relationships between LCC/P, terotechnology and TPM (source: Nakajima, 1988)

intended functions to its owner. Kelly also defines maintenance in terms of sustaining the reliability of functions, and we have no quarrel with that as an aim. However we assert that it should not be the sole aim, and that maintenance is principally an economic rather than solely a reliability problem.

RCM is a child of the aircraft, and more particularly the airline, industries. Civil airliners generally have redundant machinery and control systems, and structures which are designed to tolerate minor damage without danger. Operators found in the 1950s that increasing the frequency of overhauls to engines and other machines did not increase reliability. The US Federal Aviation Authority's (FAA) 1960 investigation was to analyse the factors affecting reliability and in particular the efficacy of PM. It "confirmed" that "scheduled overhaul had little effect on overall reliability of complex items unless there was a dominant mode . . .". This of course is nonsense from a technological viewpoint. It arises from misconceptions about the bathtub curve. We can be sure that they never tried operating the aircraft entirely without such overhauls! If they had, they would have found that the reliability fell. They apparently did not investigate the quality of the workmanship, specifically the introduction of new faults at PM, as a reliability factor either in 1960 or in the later investigations leading to the formulation of RCM. Moubray's (1991) book, for example, implies several times that the system or machine bathtub curve (ROCOF v. machine age) is inherent, when it is obviously shaped and scaled by the maintenance policy, and should not therefore be used to set the policy. More generally, the investigations were empirical and made no attempt to reconcile wear-out and age renewal theory at the component level with apparently Poisson failure patterns at the machine and system levels. This was an excusable error in 1960, given the state of the art of reliability theory, but has since been de-bunked by Ascher and Feingold (1984) and Sherwin (1997). It is true now, though possibly not in 1960, that some electronic systems are best left alone, because either they are inherently reliable due to the low, smooth, loading, or have very low constant or falling hazard rates because failures are due to residual manufacturing quality faults and random voltage peaks. However, given the need to save weight in aircraft, failures due to progressive effects in mechanical components, such as metal fatigue, corrosion, wear and creep are inevitable and are all amenable to either condition monitoring, inspection whilst stopped, or periodic maintenance or renewal. But it is components not systems which, given good data, are amenable to PM optimisation, as discussed above.

The diminishing or reversing returns effect noted in respect of reliability under increasing overhaul frequency probably arose as follows. Some overhaul routines call for inspection and renewal of worn parts according to the judgement of the technician, others for renewal regardless of condition, still others for an exchange with a machine withdrawn from another identical system and overhauled at leisure, but none for the complete renewal of the machine which would justify RCM's arguments. In the first possible case, the judgement actually made is whether there is a high probability that the part will endure to the next opportunity for renewal, so there is a built-in tendency to renew at about the same intervals regardless of the frequency of checks, provided that this frequency is above the minimum required to prevent the required high proportion of failures. In both this and the other cases, there is a proportion of bad quality parts fitted, which fail early, and also a proportion of badly fitted renewals (poor workmanship). These are reducible by quality control and training, but are often not seen for what they are because of the confusion between component and system bathtub curves, and so can appear to give diminishing or negative reliability returns from more frequent overhauls. However, with good work and good spares, in theory, reliability would increase continuously, albeit with diminishing returns, as overhaul frequency was increased. There would, of course, be a turning point with respect to availability. See Sherwin and Lees (1980) for an analysis of field data confirming the theory above.

The other important "finding" of the 1960 investigation was that, as Moubray puts it "... there are many items for which there is no effective form of scheduled maintenance". This is a direct indication that the bathtub confusion dominates RCM thinking, and this is confirmed by the reference to the need for "a dominant mode of failure" for overhaul at regular intervals to be an effective policy. In our experience, all components (except those which are intrinsically reliable under the prevailing operational conditions and therefore need no maintenance), either give detectable signs that they are about to fail, or else fail according to distributions of failure times from new which have rising hazard rate function averages. Overhaul is not the best policy unless down time is expensive relative to spare parts, so all parts that wear out rapidly should normally be renewed, regardless of appearance.

However, perhaps the worst aspect of RCM in the present context is its refusal to face up to the need for data. Indeed, several RCM investigations of which the author has knowledge have assumed that no failures recorded means no need for PM, ignoring the possibility that the PM in force has been keeping away the failures. Resnikoff's conundrum (Resnikoff, 1978) that when data are really needed, in respect of very serious failures, they are never available because one dare not let the failure happen, ignores two vital facts. First, very serious failures are often coincidences and data for the two or more events involved can be found. Second, removals without failure are also data. Censored data are evidence of reliability just as uncensored data are evidence of unreliability. The reverse Resnikoff proposed by Moubray is also nonsense. It may be that much data becomes available about less serious failures, but it is wrong to aver that as these failures "do not matter very much", the data are useless and the PM not worth optimising. All failures matter, even those to redundant parts, which would not have been duplicated if their failure did not matter. If a part does not matter it should not be there to fail. Small savings from many parts add up to a big sum, and if the data are available it does not take long to solve the equations of optimisation.

RCM also perpetuates the myth of over-maintenance. This was effectively refuted by Sherwin and Lees (1980). Maintenance only increases system ROCOF if it is badly done, causing early failures whilst mending previous ones or carrying out PM. Analysis for serial correlation is needed to discover this phenomenon since no maintainer is ever going to write under "Cause of failure", "because I made a mistake last time".

If the failures come in bunches on a calendar time-scale, bad work or bad spares are the most likely explanations, in that order. On a Weibull plot it may appear that $\beta < 1$, but if more data are awaited and analysed, it becomes clear that there are two modes, one for the errors and one for the true failures. Figure 6 shows various patterns of serial correlation which have been found in data arising from parts with and without PM, none of which are discussed in books on RCM (Sherwin and Lees, 1980).

The popularity of RCM probably depends mainly upon its not requiring any significant input or investment from higher management. In fact they are told by its proponents that savings are to be expected in the maintenance budget. RCM tries to deal with reliability and maintenance in relative isolation from costs and profits. It contains many good ideas, most of which appear in other methods also,

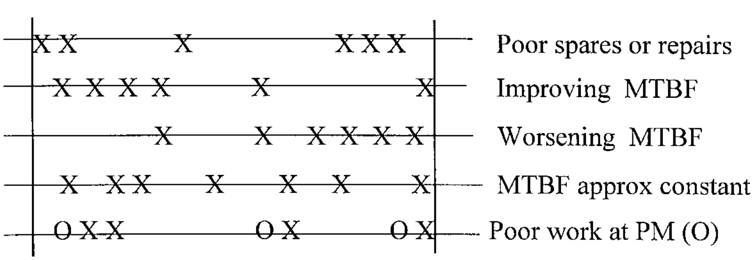

Figure 6.
Common patterns of serial correlation of failures

such as FMECA, but also some erroneous concepts like the Resnikoff conundrum, most of which are unique to RCM, the notable exception being the misconstrued bathtub curve, which is unfortunately only too common in both difficult mathematical models and simplistic analyses of maintenance needs.

Concluding remarks

Need for better IT

It is a principal objective of this paper to advocate a better way of managing maintenance by optimising schedules and integrating the maintenance function with the rest of the company's activities through advanced IT. This is now feasible and probably economically viable. What we are suggesting is selection, extension and deepening rather than denial of the work of Geraerds, Kelly and the others outlined above. In our view, technology, particularly production technology, is advancing too quickly for us not to learn from these older methods and move on to something more appropriate to the age of advanced IT. We present this as opinion for the moment, but we are busy justifying it by research, which involves finding non-controversial ways of measuring the benefits of data-based optimised maintenance to set against the costs.

The managerial de-layering of industry has left it without middle managers with time to think. The computer is now programmed to produce automatically the reports these middle managers formerly compiled by hand, but their other tasks were either forgotten or also assumed to have been automated, or to have been unnecessary. The result is overworking of the remaining managers, and a declining quality of decision making induced by a combination of hurry and paucity of accurate and appropriate information. This leads to downsizing, corporate re-engineering and all the rest of the excuses of the modern managerialism for commercial defeatism. Complete automation is of course not possible for any quasi-managerial function unless perfect data are analysed and processed through a perfect model. True managerial decisions require human judgement (i.e. guesswork informed by experience and supplemented by partial calculations based on data and knowledge), by definition of "managerial". It is not so much that the decisions themselves must become automatic as that they must be taken more quickly by fewer managers who must therefore have better information provided by a more complex and integrated IT system, capable of suggesting answers by calculating the results of self-generated alternatives. Because a computer cannot make judgements but only calculations, the input data must become more detailed, so that the modelling can be more accurate and the answers sufficiently precise to choose rationally between alternative policies.

The overall integrated company IT system of the future must suggest how matters may be improved as well as pointing out where they are unsatisfactory. This involves why as well as what is wrong. It should therefore be geared for never-ending improvement using feedback control through a network of connected Deming P-D-C-A loops, rather than just measuring the "performance" of individual departments against artificial targets fixed according to MBO principles.

Value is added or subtracted by the operation of policies agreed by the managers. We therefore suggest that the criterion of merit for changes and comparisons under such a managerial system, supported by advanced IT, should be nett contribution to life-cycle profit, (LCP). In order to manage better, companies need to be able to identify the effects of actions taken and omitted in terms of LCP, and also to take a long view, well beyond this year's "bottom line". The latter requirement implies that the reasons for not achieving outcomes predicted by the data and the software must be determined by investigation and the data acquisition and software modified if necessary. Such audit procedures constitute one of the more important of the feedback loops; they explore the practical limits of computer-assisted decision making and improve the performance of managers in the interpretation of the hard information available.

The benefits of advanced manufacturing technology cannot be realised fully without an IT system that permits decisions, including maintenance decisions, to be calculated rapidly through realistic models using credible data. In another paper, we hope to explain what these requirements imply in terms of IT system structure and managerial style. The present paper is to be taken as "proof of need" in the sense of Juran's writings (see for example Juran, 1981).

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