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Asset Management: A Maintenance Engineer's View

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Abstract: In the past, assets were designed in large construction teams but companies in recent decades focus more and more on their core activities. The management of capital goods is being organized in the (supply) chain of owners, users, manufacturers, research institutes, IT, service providers and so on.
The complexity of modern systems (*e.g.,* mechatronics) and sustainability issues have placed more pressure on cooperation: openness, interaction and stability in the relationship foster joint innovation in product, process and technology. Focus on opportunities rather than risks makes this cooperation successful.
With the operational processes in good shape it is to show where the technical characteristics of the assets fail. Technical "on the spot" support is important to develop understanding between the maintenance and the production organizations, and establishing a sense of urgency in their cooperation: first to analyze the actual fault behaviour of the equipment and to solve short-term problems and secondly to take structural measures.
In the coming years, real time monitoring facilitates maintenance with more accurate information than before. Proactive dynamic maintenance scheduling reduces the number of unexpected failures.

Keywords: *Asset management, maintenance engineering, life-cycle costs, design for maintenance, supply chain cooperation, monitoring*

1. Introduction

Optimal management of capital goods is vital in terms of satisfying the need for sustainability, safety and reliability in society. Moreover, the expenditure associated with the maintenance of production equipment often amounts to several times the investment costs. Maintenance is a "wide-ranging subject" that must be reviewed during the entire life-cycle of an installation: from initial definition of the requirements, design, implementation, use, overhaul and modernization to dismantling (see Figure 1). In other words, collaboration between designers, managers, mechanics, operators, economists, regulators and investors is important for optimizing the performance of operational assets in line with the life-cycle costs.

In this respect, it is essential that the various disciplines involved collaborate from the point of view of having a common interest in the chain, not only inside, but also outside the company. The technical design of an installation must have a maintenance concept. In accordance with this concept, production managers can then prepare, plan and execute the required activities. It is fairly obvious that performance can only be enhanced and costs can only be reduced with joint efforts for these disciplines. The nature of maintenance concepts that, up to now has been quite static, is becoming increasingly more flexible due

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to the large-scale implementation of sensors and digital diagnosis and control systems. This enables the current maintenance requirement to be determined online, maintenance tasks to be planned and even defects to be predicted on the basis of trend analysis.

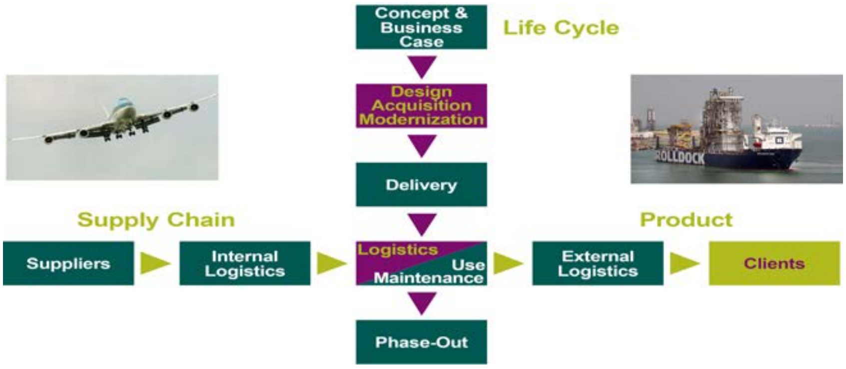

Figure 1: Life Cycle of Capital Assets

2. Maintenance: Self-evident, Unseen and Indispensable

People, simply continue to make intensive use of “public” capital goods: buildings, roads, bridges, waterways, locks, dykes, ships, aircraft, trains, public utilities such as water, gas and electricity and, of course, the increasingly more important IT infrastructure. It is taken for granted that the availability of these facilities is guaranteed, and that environmental risks and safety risks are managed during the entire life-cycle. The awareness of the public is only raised in the event of disruptions, in the event of serious accidents, or when the politicians, policy makers and/or stakeholder organisations enter discussion with each other in relation to major investments in, for example, electricity generation: choice between coal, gas, wind, solar, hydropower or nuclear fuels.

For example, in the train disaster involving ICE train 884 (“Wilhelm Conrad Röntgen”) between Munich and Hamburg on 3rd June 1998, the train was derailed beside a viaduct in due to a broken wheel. Seven carriages were so badly damaged (see Figure 2) that 101 passengers were killed.

Figure 2: ICE Accident

Investigation revealed that a combination of material properties, design faults and maintenance errors caused a fatigue crack in a wheel. "Early warning" signals relating to this fatigue crack were disregarded. This can partly be attributed to the fact that German Railways ('*Deutsche Bahn*') gradually transferred the responsibility for designing rolling stock from its own technical stronghold to industry.

After investment decisions have been made, the intrinsic quality in the design of installations is determined on the basis of Failure Mode Effect and Criticality Analysis (FMECA). This "quality as built" can be kept within acceptable margins. During maintenance, the behaviour is measured, recorded and analyzed using "customized maintenance" in order to guarantee operational reliability, availability, maintainability and safety (RAMS). Techniques such as Reliability Centered Maintenance and Risk Based Inspection are used for this. A balance must therefore be reached between designed quality and the maintenance required. Economizing on the design quality cannot be compensated for later –with extra maintenance.

On the other hand, the quality of a well thought-out and possibly slightly more expensive design can, with the correct approach, be implemented with lower maintenance costs, thus resulting in optimal Life-Cycle Costs (LCC).

As shown in Figure 3, the intrinsic characteristics of capital goods are determined during the initial design and possibly during modernization. Since the life-cycle of capital goods usually exceeds the average employment period, employees (managers, designers, operators and mechanics) experience the benefits and burdens attributable to their predecessors. Working and acting with the inner conviction that you are responsible for the future of the next generations of colleagues is an important key to success. Moreover, the long-term approach for investments in capital goods also requires stability in politics and government, in the public sector as well as the private sector. It is essential that science, technology and social development go hand in hand. Due to the demands for social safety and sustainability, RAMS "**H**ealth & **E**nvironment" (RAMSHE) is nowadays added to the technical life-cycle parameters.

Whilst technicians shaped welfare from the industrialization up to and including the reconstruction after the Second World War with their professional contribution, during the last few decades of the previous century they were superseded by sociologists, lawyers, politicians, economists and investors who determined the developments in society. The new generation of engineers must be able to understand the language of other disciplines, participate in public debate, and know how to match its designs to the sustainability requirements of the environment.

Safety, availability and reliability are not only guaranteed by technically perfect designs and maintenance concepts. The attitude of managers, operators and mechanics determines, to a great extent, the final result. Well-defined procedures, work instructions, working conditions, *good housekeeping*, job descriptions, tasks and responsibilities are also required. This is in keeping with a culture in which employees are empowered to report unsafe working conditions, technical problems or lack of clarity in the organization, and to take measures: not only in the own working environment, but also in the hierarchy of the organization. Open communication enables significant progress to be gained: work only takes place if the conditions are unambiguous and safe. The less dominant the blame culture is, the faster the risks are highlighted and dealt with.

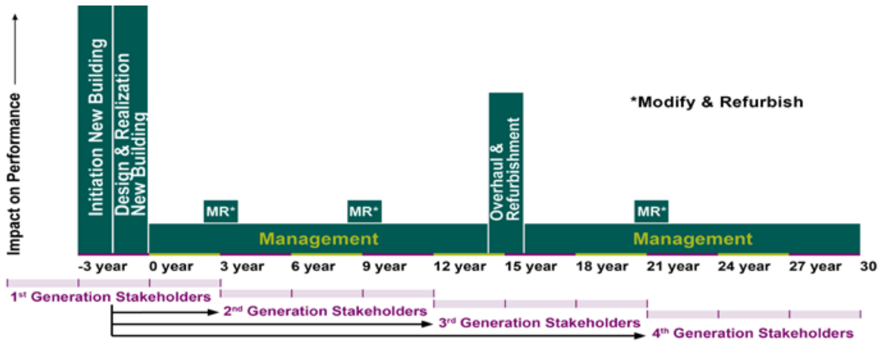

Figure 3: Initial Design determines Performance over the Life-Cycle

The risk lies in the routine careless behaviour that results from pressure caused by external factors, and can have major consequences. For example, on 6th March 1987, the Herald of Free Enterprise, already late for departure, left Zeebrugge with full ballast tanks and an open bow door (contrary to regulations), took on water, and then capsized.

Market research into Dutch machine park (conducted by Mainnovation and TNS NIPO) indicates that 92% can be regarded as being reliable. However, technical failures cannot be ruled out. Technical failures are mainly caused by economizing on investment in compromise of quality, end of service life, savings in the maintenance budget, or a backlog in the maintenance program. It could be assumed that the management involved in this informed decisions factor the risks relating to downtime and safety. It may not be concluded from this research that 8% of the machinery is unsafe.

Effective management of capital goods is based on the correct use of technology, well-considered decisions in terms of maintenance, a well-structured open organization, and robust operational management.

3. Economic Importance of Maintenance

In terms of safe, optimal, reliable and affordable operational management, maintenance is an important field of activity in industry and in public services. An overview from the University of Twente (commissioned by World Class Maintenance) illustrates the importance of the Maintenance, Repair and Overhaul (MRO) industry. The total value of capital goods in the Netherlands is estimated to be 400 billion euro. Each year, 18 billion euros are spent on maintenance, a function that employs 150,000 people (mechanics, maintenance engineers, work planners, accountants, supervisors, warehouse employees, purchasers, contract managers, *etc*.). With roughly twenty thousand professionals due to retire in the coming years, there is a great opportunity / challenge for establishing the field of and training maintenance technicians and specialists.

With regard to the management of capital goods, during the life-cycle, several times the investment costs are often spent on cyclical maintenance, overhaul, modernization and life-cycle extension. Figure 4 provides an overview of the investment costs for various operational assets and the capitalized maintenance costs. For example, a Joint Strike Fighter costs 60 million euro, and during a period of thirty years, 120 million euro is spent on maintenance. The larger, more complex and more expensive an installation is, the greater the amount is for maintenance costs as part of the total life-cycle costs. That means that the total costs for an installation also constitute a substantial part of the products' costs.

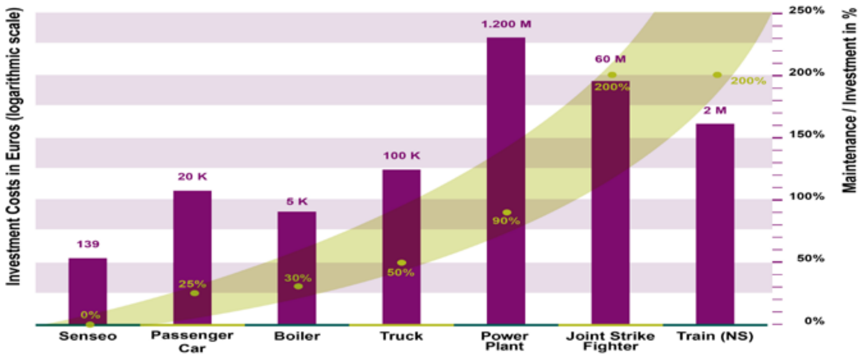

Figure 4: Maintenance Costs are Several Times the Investment Costs

It is important for the Netherlands Railways ('*N.V. Nederlandse Spoorwegen*') to find the correct balance between the investment costs and the other operating costs. Passenger rolling stock costs roughly 2 million euro per carriage.

With 3,000 carriages in service, the replacement value of the fleet amounts to approximately 6 billion euro. The total value chain of the domestic passenger transport is 1.65 billion euro annually. Figure 5 provides an insight into the components of the operating costs.

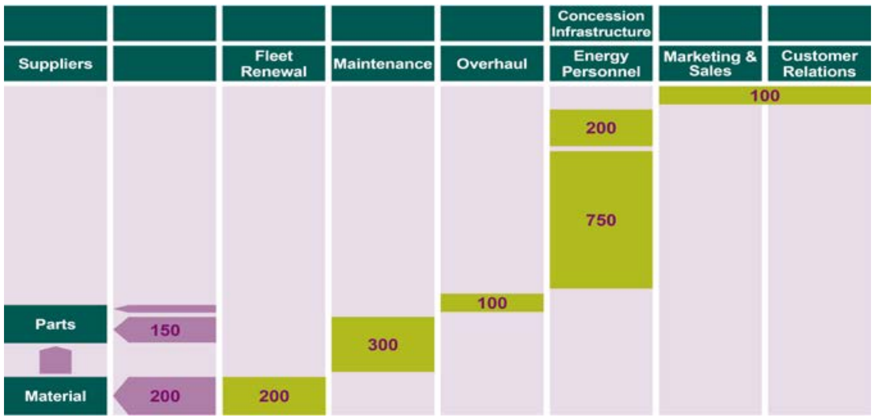

Figure 5: Large Cost Share of Operational Assets in Operating Account

As a rough guide, during recent years, 100 carriages per year (200 million euro) were delivered. In view of the significant amount in the total costs, at first glance, it seems to make sense to keep these investment costs (12%) low. However, reality is obstinate: the maintenance costs for the fleet have risen to more than double the investment costs: 300 million euro for cyclical maintenance and the overhaul of parts, and 100 million euro for the overhaul and modernization of the carriages: in addition to the initial investment costs, *i.e.*, 24% more. The share of the costs of rolling stock in the operating account thus amounts to 36%. [1]

[1] In view of the recurrent pattern of spending, the investment costs are included as depreciation costs in this overview for the sake of simplicity.

In other words: the combination of initial investments and RAMSHE costs determines the total life-cycle costs. It is self-evident that these costs are dependent on each other: the amount of maintenance and overhaul work is determined to a great extent by the design quality of the initial investment: RAMSHE and LCC aspects must be considered and introduced during the design phase. Based on prudential considerations, the correct decisions can be made and account can be taken of maintenance experiences in order to create value for the operational management.

4. Collaboration at the Interface of Design and Maintenance

In the past, operational assets were designed in various sectors in construction teams with technicians from the own production organisation and suppliers to whom the construction was outsourced. The full scope of availability, reliability and costs, together with the technical specifications, was perhaps implicitly still considered to be of paramount importance. Collaboration took place in accordance with the Rhineland model (‘*Rijnlandse model*’) with strong dominance for technology, and sometimes even with technical innovation as an additional objective. Although the installation was provided with comprehensive technical specifications beforehand, during the design phase, the client contributed his experience during the evaluation of the construction drawings, and the construction was finally agreed with “design freezes”. The owner/user thus received technical know-how from the subcontractors via the main contractor. This provided the client with sufficient knowledge to compile the operating and maintenance instructions based on the documentation supplied. Moreover, this also enabled solutions to be found for teething problems during the putting into service.

At the beginning of the 1990’s (in order to cope with the traffic generated by the introduction of the student card), the Netherlands Railways (‘*NV Nederlandse Spoorwegen*’) purchased 286 double-decker carriages and 81 locomotives of an existing type (because rapid delivery was required). When, several years later, the need for new locomotives for the intercity traffic and the rail freight became evident, a business case was outlined for replacing a number of locomotives in the suburban double-decker trains with “customized” motorcars that were just as expensive as new multifunctional locomotives, but equipped with 55 seats (see Figure 6). Based on functional/technical specifications, their construction was contracted out to a main supplier and several subcontractors selected by the Netherlands Railways (NS). Intensive collaboration with the industry at that time meant that a reliable business case could be drawn up. When implementing the project, minimal discussion was required in order to understand each other and collaborate in a goal-oriented manner. Engineers from the Netherlands Railways sat round the table during the design phase, and during the manufacture, acceptance inspections were performed at various factories and active collaboration took place focused on putting every train into service. Despite a few initial teething problems that were solved at the time, these trains are still operating satisfactorily on the Dutch railway network’.

Figure 6: "Customized" Trains

The other side of this picture is that technical innovation was often necessary, and the client was also expected to give certain guarantee commitments. At the time, the same procedure was also common in other sectors: for example, the Provincial Electricity Companies ('*Provinciale Elektriciteitsmaatschappijen*') that collaborated at technical level with the SEP and the KEMA. Philips NV, with the Philips Physics Laboratory ('*Natuurkundig Laboratorium*') and the Centre for Manufacturing Technology ('*Centrum voor Fabricage Technieken*'), was also inspired by the "technology push".

During the past few decades, the privatization of public services has prompted companies to focus more on their core activities. Quite rightly, the customer occupies centre stage and the focus is on product development. The development and the management of capital goods are set aside in the chain. Owners, users, designers, knowledge institutes, IT and service providers collaborate in terms of design, management, use and maintenance. Suppliers of large installations have expanded as "System Integrators" into companies that, together with subcontractors, develop and offer systems and installations based on (their own) market insights and technical experiences.
When becoming acquainted with these new circumstances, knowledge of maintenance and the production process and technical design is indispensable. However, all parties are reluctant to share this knowledge because the work is performed in different roles: for example, in one project as a colleague in a consortium, or in another project as a subcontractor in competition with third parties.

The focus on quality and life-cycle costs is limited to tangible specifications for functional wishes and performance, without integrating production experiences in the design from the supply industry. The knowledge of the technical content often remains with the (sub)contractors. This presents the risk of it being increasingly difficult to determine the required maintenance or to implement changes to the construction autonomously. This trend is highlighted by the guarantees that clients want to impose in elaborate legal contracts. The supplier shall only give guarantees if the maintenance is performed in accordance with the instructions from the supplier. Due to the guarantees obtained, the ability to negotiate is limited during the guarantee period. Cost savings achieved by developing the maintenance plan can only be realised later.

In this chain, the collaboration is often based on shifting responsibilities and risks in accordance with the Anglo-Saxon model. Compensation and fines are the main incentives in this respect. Moreover, the prospect of "easily-earned" money (in shareholder value as well as in rewards and bonuses for the management) in the short-term, is appealing. This results in only the information that is really relevant being exchanged.

When purchasing the Sprinter Lighttrain, mainly based on the functional specifications, the Netherlands Railways (NS) and the Bombardier / Siemens consortium finally decided to delay the project for several weeks during the construction phase in order to implement a number of construction changes relating to the maintainability of the equipment. Well-planned assembly of the trains does not automatically imply that the design is efficient and effective in terms of maintenance.

The position of the compressor under the train has been modified so that it can be replaced using a lifting table in the pit track. Specials tools were developed for disassembling the traction motor so that it can be changed underneath the train.

During the commissioning phase, the maintenance schedule for the trains was optimized in mutual consultation. For example, ultrasonic inspection of axles was not performed based on time, but on the number of kilometres travelled. The content of the 7-year overhaul must still be determined in mutual consultation.

The industry is dependent on companies such as NedTrain for the implementation of optimal performance and the acquisition of information. On the other hand, maintenance firms also require technical documentation from the (sub)contractors for their activities. All of the market parties must thus continue to collaborate during the entire life-cycle of the equipment.

The fact that inadequate communication relating to details of the work to be performed can result in misunderstandings (for example, between road administrators and contractors) is highlighted by Figure 7: new traffic signs were installed without removing the old signs.

Figure 7: Contract Management: Input, Output of Process?

The question here is whether this relates to an input, output or process contract! It is possible that (based on details that were not adequately considered) the contractor has intentionally not included the removal of the old traffic signs in his offer so that he does not “price himself out of the market”. Evidently, a discussion about mutual expectations never took place! The new Tunnel Act (‘*Tunnelwet*’), new types of contracts, an unclear division of roles between the client and the contractor, and inadequately described functional details were the causes for the delayed delivery of the underpasses for the A73 motorway at Roermond and A2 motorway at Leidsche Rijn. Although, in the past, it was customary for the Dutch Ministry of Waterways and Public Works (‘*Rijkswaterstaat*’) to manage large projects, in both of these cases, the role of “system integrator” was assigned to the contractor without these competences being adequately developed and without these new relationships being optimally elaborated. In particular, the detailed insight into the function and technology relating to the safety system has resulted in a great deal of uncertainty, extra work, redesign and disruptions during that collaboration.

New developments such as the sustainability and complexity of systems (for example, mechatronics) will impose new requirements in terms of collaboration in the future: openness, mutual communication and stability in the relationship will stimulate the joint innovation of product, process and technology. The focus on mutual interest and opportunities, instead of on individual gain and risks, will lead to success. Maintenance expertise and experience, that do not apparently provide any short-term benefits, and that are also not stated in the accounts, determine the development potential and play a key role in forging the link in the innovation chain.

5. Key Position of the Maintenance Organization in Asset Management

Maintenance plays an essential role during the entire life of an installation: from idea, initiative, business case, investment decision, acquisition, design, construction, delivery, use, cleaning and maintenance, to removal and dismantling. The various stakeholders shown in Figure 8 collaborate in that chain. Products and services are produced by industrial production equipment. In view of the levels of investment, implementation deadlines, life-cycle and sustainability requirements, it is inevitable that the parties involved, such as government, politicians, consumer organisations and supervisors interact in a stable manner, taking into account every interest so that, in those circles, product development can finally take place.

On the supplier's side, technical innovation takes place in collaboration with various parties, including knowledge institutes, engineering firms, architects, specialists, subcontractors and "System Integrators".

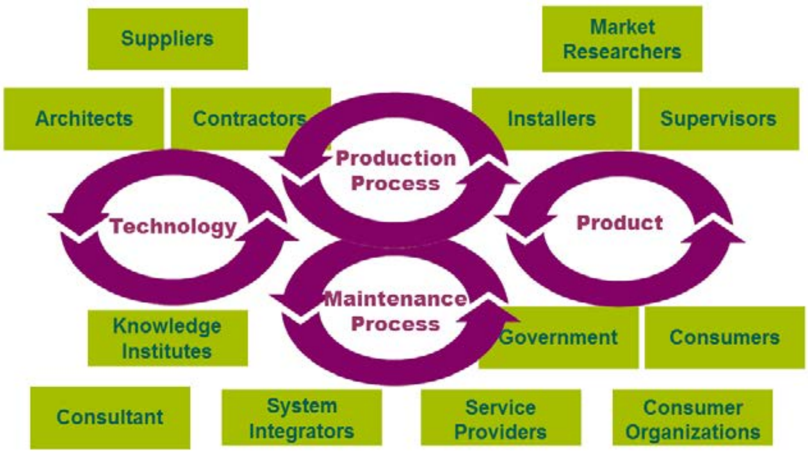

Figure 8: Chain of Innovation

The production organisation and the maintenance firm operate at the interface of these worlds: using the technology supplied, they jointly produce the desired product. Their experiences from the production processes enable them to specify how the technology should be implemented in designs. It is also fairly obvious that these innovation circles of technology, process and product (if optimally completed) form the basis for professional asset management. The maintenance organization plays an important role in this respect.

Maintenance is sometimes regarded as a necessary evil. This view is understandable if it is inevitable that basic maintenance must be performed. From the aforementioned paragraphs, it is clear that suppliers, system integrators, operators and owners benefit from the knowledge that is available in a maintenance organization.

Maintenance Engineering is the subject that, at the interface of various disciplines, enables a maintenance concept to be drawn up for an installation. Maintenance Engineering optimises this concept, taking into account (i) the advances in monitoring the behaviour of the installation, (ii) the operational wishes and requirements of the production organisation and (iii) optimal cost management, in order to create value for the company.

If maintenance engineers play a more prominent role during the entire life-cycle of capital goods, this will create an optimal balance between suppliers, owners and maintainers. Such a new balance illustrated in Figure 9 will clarify the assignment of tasks to the relevant organization, thus enabling a more targeted approach to the integral management of capital goods from a maintenance perspective in the decision-making.

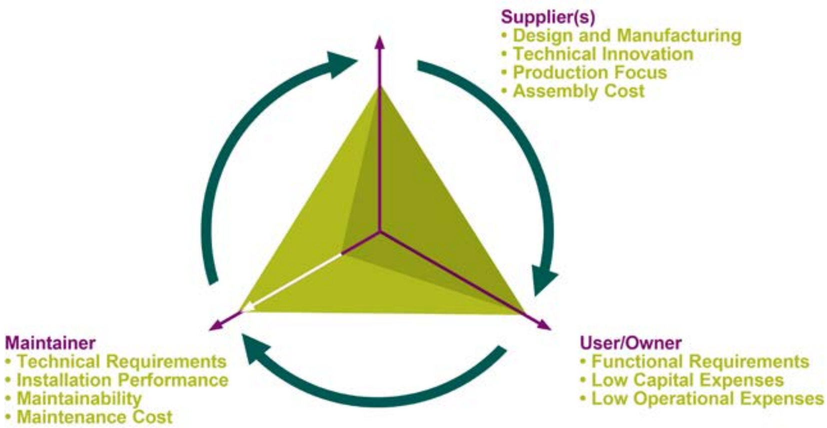

Figure 9: Integration Approach for Performance during Life-Cycle

The owner/user of an installation needs to have correct functional performance and low costs, not only in terms of capital costs but also operating costs: energy consumption, availability, reliability and maintenance. The maintenance organization is able to transform these functional requirements (via “System Integration”) into technical requirements, not only in terms of the performance of the installation, but also in terms of maintainability. The contractor uses the available technology to design and construct the installation at the lowest possible cost. It is obvious that an integral optimum can only be attained on the basis of interactive considerations and joint decisions.The modern maintenance organization – as “Maintenance Integrator” – links the technical disciplines in the chain, bundles information flows, joins the links and directs the management of the capital goods.

6. Optimization of Installation Performance

Maintenance can be described as the combination of all technical, administrative and management tasks that are required to maintain an installation or restore it to a condition that enables the desired function to be fulfilled. This is necessary because the condition deteriorates due to degradation of components and systems. Under ideal circumstances, the condition is known or predictable and the maintenance can be performed at the correct moment. However, in practice, this is not always the case, due to inadequate information, insufficient knowledge, and logistical and operational limitations.For modern installations, an initial maintenance concept is drawn up (parallel to the technical design), including daily and short-term maintenance as well as long-cycle maintenance schedules for minor and major overhauls, based on Reliability Centered Maintenance (RCM) and Failure Mode Effect and Criticality Analysis (FMECA) in an overview of clustered tasks. This is completed with a description of what is required for this in terms of requirements from the employees (knowledge, experiences and possible certification), information and documentation, operational assets and tools, and finally, the correct parts.

Maintenance tasks are classified as preventive maintenance or corrective maintenance. Preventive maintenance is subdivided into two categories: usage-dependent and condition-dependent maintenance.

In the case of use-based maintenance, tasks are determined by:

- either the time (independent of the actual condition of the installation) which inspections and activities must be performed at specific intervals
- or the actual number of kilometres, operating hours or starting cycles at which replacements, maintenance and adjustments are necessary. Such maintenance operations are often compiled on the basis of experience and research into degradation behaviour.

In the case of condition-dependent maintenance, the condition (measured in accordance with established standards) to be ascertained via an inspection determines whether replacement, maintenance or adjustment of components or systems is necessary. The inspection is planned in accordance with a fixed frequency, but the maintenance activities to be performed are only planned afterwards.

Corrective maintenance is necessary in the event of a fault or defect. If a defect does not have any direct consequences for the primary function of the installation, the defect is rectified during scheduled maintenance. In the worst case scenario, a fault must be immediately rectified, and this has implications for the availability of the installation.

The behaviour of an installation is measured: performance, usage data, fault behaviour and the like, are registered and logged in handwriting or directly in digital information systems. The timely information about the maintenance requirement enables the current work to be planned. Moreover, analysis of the data enables links between the maintenance work and the use of the installation to be ascertained. These detailed insights enable the maintenance plan to be continually optimized. Even though a maintenance concept seems to be fixed, it can be modified by virtue of experience. For example, more preventive maintenance in order to achieve enhanced reliability, or less maintenance (within the system technical limits) in order to save costs. Preventive maintenance for mechanical components can be optimally determined on the basis of maintenance research: for example, degradation behaviour in relation to use. The condition can also be directly ascertained by measuring physical parameters on the construction of the installations. For example, the thickness of brake linings in the case of condition-based maintenance.

In the case of overhaul or modernization, relevant experience can be used to technically enhance an installation. If necessary, construction changes can be implemented, as required.

Figure 10 provides an insight into these control loops:

- *Design for Maintenance*. At strategic level (long-term decisions and investments), it is important to have the optimal resources available: suitable installation, correct configuration information, adequate infrastructure, machines & tools, an initial maintenance concept and an optimal training program for the operators and the mechanics. In other words: does the organization have the correct resources?

- *Maintenance Engineering*. In the medium-term, every effort is made to ensure that the correct maintenance is performed. The recorded faults are analyzed, trends are measured and corrective actions are determined. The maintenance concept is modified as necessary: if required, the execution quality is discussed with production managers, or the quality of the components is discussed with suppliers. This relates to tactical improvements to the long-term management of an installation.
- *Maintenance Management.* The work required for the short-term can be planned: inspections, cleaning, maintenance, repairs, supply of parts and planning of personnel.

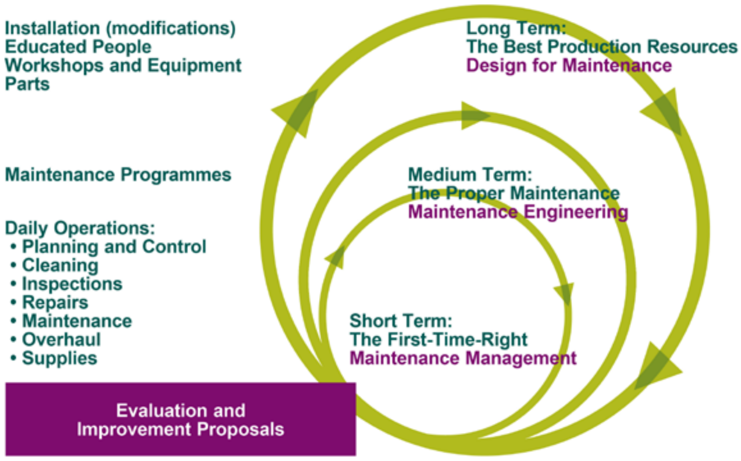

Figure 10: Maintenance Process Improvement

Maintenance is not only limited to performing maintenance tasks. The strategic and tactical improvement activities described above enable maintenance to be transformed from an inevitable cost into a value generator for the company.

7. Monitoring: The Heart of the Dynamics

Up to now, degradation behaviour has been monitored “in the rear-view miror”. Efforts to modify and optimise maintenance plans have been relatively slow. In the case of installations with mechanical systems, this is obvious, because degradation due to extrapolation is predictable. In cases, where large numbers of the same systems or installations are in use (for example, aircraft, trains and compressors), statistical analysis can be used to determine the maintenance requirement.

Modern installations, equipped with a lot of mechatronics and digital control systems, have so much data “internally” that information about the technical condition of the installation can be retrieved via displays. Moreover, where necessary, targeted monitoring with sensors can also be performed: for example, vibration sensors on critical bearings. Monitoring entails more than just finding or diagnosing a fault. Monitoring can (by recording and analysing changes in the relevant parameters) also provide an insight into the degradation behaviour before a fault actually occurs.

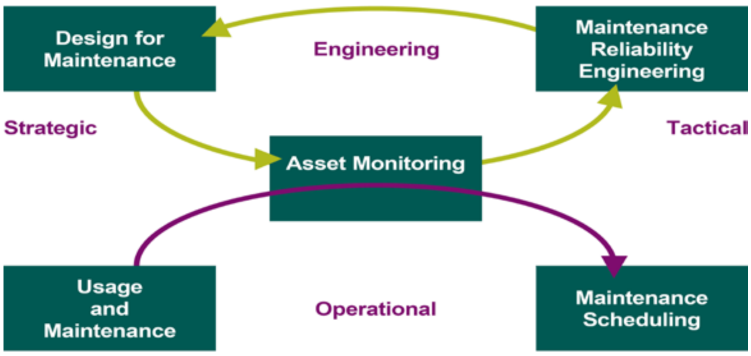

Figure 11: Monitoring: Heart of the Dynamics

This is only possible with "on the spot" monitoring, but also with remote (wireless) data communication. By using these techniques, the current maintenance requirement can be determined and the work can be planned: targeted service work in the short-term, and clustered maintenance in the long-term, at a moment when this is convenient for the production organization. Reliability engineers (who are responsible for the operational safety of an installation) can give repair or maintenance advice from the control room before a fault occurs.

Monitoring and automated processing of the data enables more accurate information to be obtained than in the past. Monitoring facilitates the (previously described) management of capital goods at operational, tactical and strategic level (Figure 11).

Maintenance has been transformed from statistic, mechanic, reactive, logbooks, oil, greasy hands and cost-center, to digital control technology, electronics, proactively focused on the future, flexible, dynamic and providing value. Thus, Real Time Monitoring is the key! Dynamic maintenance based on the current condition requires flexible maintenance logistics. For this, it is necessary to develop software that can interpret the current condition and can modify plans, without affecting the execution.

Whether an organization needs a dynamic flexible maintenance program, or can suffice with a star programme for the entire installation, or a mix programmes for large components in combination with condition-dependent maintenance, depends on the wishes and abilities of an organization. This explains the large differences in maintenance programmes for aircraft, ships, trains and power stations.

8. Technical Teams Close to the Work Floor

When managing an installation in accordance with the (previously-described) short- and medium-term approach, it is important that the production department and the technical staff collaborate intensively with each other. This is based on well-organized use and maintenance in accordance with the approach from Kaizen, Six Sigma, Lean Working and First Time Right. This involves an orderly arrangement of the processes, quality procedures, safety policy, training, certification, job descriptions and so on. It is necessary to have the operational processes correctly in place in order to be able to show where technology fails. Technical support for the production organisation must be given "on the spot" so that maintenance/reliability engineers, operators and mechanics develop an understanding of each other's work and understand the urgency by collaborating. On the one hand, in order to analyze the current fault behaviour of the installation, solve short-term problems and, on the other hand, implement long-term measures. This enables the performance of installations to remain optimal! Based on, for example, the RCA & FMECA approach, proposals for improvement are generated: modifications to the design of the installation or to the maintenance concept and improvement of the execution quality in the maintenance process are thus brought to the notice of the relevant managers.

Several years ago, at NedTrain, rolling stock teams were deployed in the maintenance workshops per rolling stock series: consisting of a rolling stock manager as “owner” with a reliability engineer, a configuration engineer, a business analyst and a maintenance engineer with the desired objectivity (regulator) as guest around the discussion table. On the one hand, they develop the operational safety of their rolling stock series and assume responsibility for the technical part in the asset management of the owner/transporter. Given the service life of the rolling stock, requirements and wishes relating to deployment, performance, maintenance, modifications and costs are determined.

If necessary, the reliability engineer modifies the operational safety objectives for the equipment assigned to him via analysis and improvement of the failure behaviour of systems and components in these systems. He initiates reliability sessions for components and indicates whether problems with suspect components need to be discussed with suppliers. From the feedback of his findings, he can propose design changes. He also brings modification of the maintenance concept and improvement of the execution quality in the maintenance process to the attention of the relevant managers; the maintenance engineer and the production manager of the maintenance workshop (see Figure 12).

Figure 12: Reliability Engineering: Spider in the Web

The reliability engineer checks the operational safety of new systems, designs and maintenance concepts and thus manages all improvement actions for his rolling stock series. The deployment of equipment teams in the maintenance workshops also means that the technology has been moved from the ivory towers to the wok floor, so that production and technology can speak each other's language!

9. Maintenance: A Multidisciplinary Subject!

Maintenance is a subject at the interface of various management subjects and disciplines with a technical content (see Figure 13). Physical phenomena (an area for special attention) with, for example, failure behaviour of components, material properties and tribology, constitute an important source of knowledge for maintenance. This, for example, relates to the operating life of bearings, corrosion of metals, ageing of plastics and fatigue of components. Knowledge of supporting technology, such as sensors, diagnosis and measurement techniques, enables effective maintenance concepts to be compiled.

Advances in the use of electronics and digital control techniques are continuing at such a high pace that the effect on operational safety, maintenance and life-cycle costs due to replacement problems is still uncertain. In practice, the software management also causes problems. This presents a challenge that requires an adequate solution.

System designs, design methods, project management and risk management are important working practices for enhancing the efficiency of capital goods.

Management aspects (organization, costs and operational management) can also be deployed in the world of maintenance in order to implement efficient operational management. Maintenance requires well thought-out logistical planning, including collaboration with the user and the suppliers of parts: logistical matching of the maintenance requirement, removal of the installation at the production, availability of maintenance personnel, supply of parts, implementation of workplaces, *etc.*

Figure 13: Maintenance: A Multidisciplinary Subject

Data processing (basis for planning maintenance activities with data from various disciplines) and operations research & statistics (operational decision models) contribute to the professionalization of maintenance.

10. Conclusions

Until recently, maintenance was regarded as reactive repair work involving open-ended spanners and greasy hands. With the increasing complexity of technical systems, the higher utilization rate of installations, the dependence of the facilities, the social safety and sustainability, the importance of maintenance is being recognized to an increasing extent.

When using capital goods, several times the investment costs are often spent on maintenance. Since, with regard to large complex installations, detailed insights are required in relation to use, degradation and performance, it is self-evident that parties continue to collaborate in an open manner. This is the case in the chain of suppliers and designers of new operational assets as well as in the case of outsourced work relating to the management, maintenance and modernization of existing installations. The dilemma between the cheap assembly of installations and efficient and effective maintenance can be eradicated by integrating life expectancy aspects in the initial design of new capital goods and also in the modernization. This will enable better performance to be attained during the life-cycle. Different technical disciplines can be combined: including electrical engineering, civil engineering, mechanical engineering, materials engineering and control technology.

Maintenance is a subject associated with linking: the modern maintenance engineer must be able, on the basis of these disciplines, to use design methodologies and analytical techniques, implement management measures, and draw up proposals for improvement. The functional relationships must also be nurtured, from designer and manager via reliability and maintenance engineers and analysts to operators and mechanics. The work of the technical staff at the maintenance workshop must focus on the primary process, in order to prevent unrelated designs and concepts from being conceived that do not work. Mechanics and operators must able to immediately report any sticking points in the maintenance to the staff engineers. The desired performance is attained by jointly measuring and analyzing the behaviour of an installation and, based on this, implementing modifications to the design of an installation, the use of an installation, the maintenance concept or the quality of the maintenance process.

Condition based maintenance and real time monitoring are next steps in providing higher performance of equipment by just in time maintenance actions shortly before failures occur. This requires flexible operational logistics in the maintenance execution.

Thinking in terms of opportunities and mutual benefits (instead of in terms of risks and compensation) is the precondition for social innovation and stimulating innovation in product, process and technology, not only within the maintenance organization, but also throughout the chain of collaborating companies.

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