The maintenance of civil engineering structures

A. VAN DER TOORN
Ministry of Public Works
University of Twente

Abstract

This paper deals with maintenance stragegies for civil engineering structures. First a description of the current primarily historically grown practice is given. Next a theoretically more advanced approach is formulated and its possible use in the field of civil engineering structures is discussed. Finally the application of the proposed procedure is demonstrated for the case of a viaduct and a sluice.

Keywords: Maintenance strategy, maintenance concept, ageing mechanism, consequences of failure, decomposition, maintenance targets.

1 Introduction

Maintenance in civil engineering is getting a more and more important topic. One of the main reasons for this development is the aging of the large group of structures, built after World War II, and the consequent increasing need for major repair and renovation activities. Additionally, either for economic or for environmental reasons, governments in nearly all countries require explicit justification of all maintenance measures, while at the same time societies require higher availability of the infrastructural civil engineering works.

As a result, more insight into and control over the maintenance of structures is desired. This statement is not only valid for the set of existing structures, but also, and may be even more, for the structures under design: maintenance should be specified in advance and become an integrated part of the design. This paper attempts to give a theoretical basis to inspection and maintenance strategies for civil engineering structures.

2 The components of a structure

2.1 *The technical description*

Consider, by way of example, a simple structure such as the concrete viaduct in Figure 1. Two main parts can be distinguished: the substructure and the superstructure. The substructure consists of two abutments with one or more intermediate supports, which are usually founded on a number of piers. The superstructure consists of prefabricated concrete beams with a cover layer of cast in situ. Between the superstructure and the substructure bearings are present, frequently made of rubber to enable certain internal movements. For the benefit of the traffic additional provisions have been made on the superstructure such as a wearing course, expansion joints connections, stop shoulders, etc.

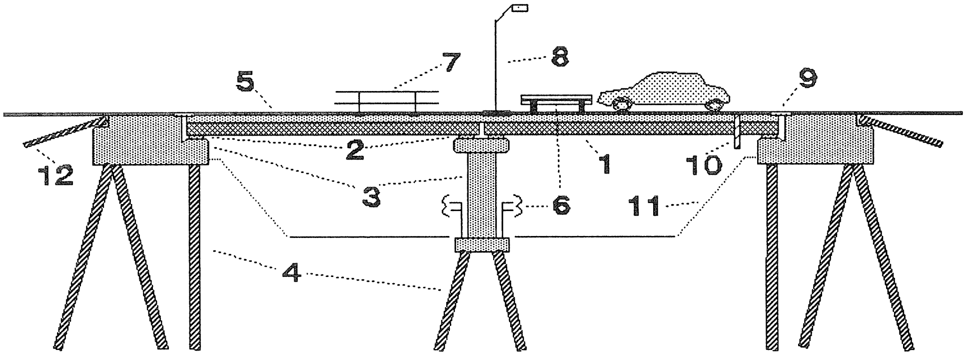

Fig. 1. The (main) parts of a viaduct: 1. Main bearing structure (beams and slab); 2. Rubber bearings; 3. Support points (abutments and intermediate piers); 4. Foundation structures; 5. Asphalt wearing course; 6. Guide rails or crash barriers; 7. Parapets; 8. Lighting; 9. Expansion joints; 10. Rainwater drains; 11. Soil-retaining structure or covered slope; 12. Traffic impact or approach slabs.

A more complicated structure, a navigation lock, is presented in Figure 2. The main parts are the upper and a lower heads, frequently supported by a large number of piles. These heads have lock gates (including slides), which can be moved by mechanical or hydraulic means. Together with the intermediate walls the heads form the lock. To prevent groundwater seepage, cut-off walls are built next to and under the lock. For the operation of the lock, there are electrical components, such as cables, switches, relays, motors, etc. and electronic parts, such as cameras, monitors and computers.

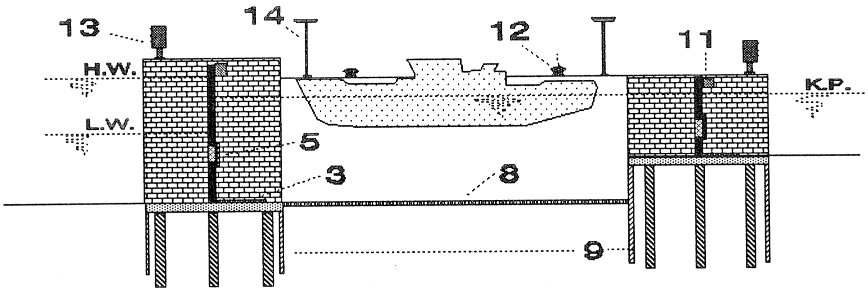

Fig. 2a. Side view.

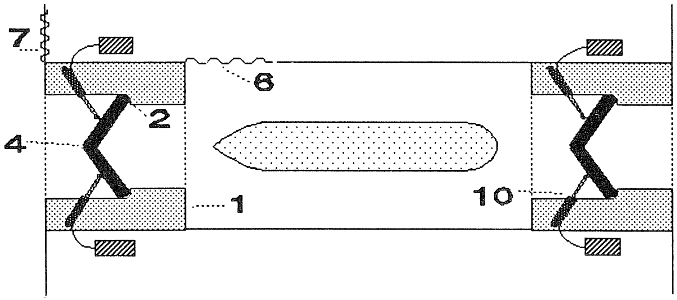

Fig. 2b. View from above.

Fig. 2. The (main) parts of a navigation lock: 1. Upper en lower heads (incl. foundation); 2. Turning points (pivot and collar); 3. Stops (bottom sill and side stops); 4. Doors (e.g. two sets of mitre gates); 5. Means of levelling (here: sliding gates); 6. Lock walls (here: steel sheetpile walls); 7. Bank protection (here: sheetpile walls); 8. Bottom protection (here: layer of rubble stone); 9. Cut-off walls; 10. Movement mechanism doors (e.g. hydraulic); 11. Movement mechanism sliding gates (e.g. mechanical); 12. Bollard recesses and bollards; 13. Navigation signals; 14. Lighting; 15. Control panel; 16. Lockkeeper's building.

2.2 *Infrastructural functions*

Structures fulfil one or more functions. As an example, bridges, tunnels and viaducts are links in the traffic route system. A weir has a water-regulating function, and a storm-surge barrier serves both to retain and to pass water. Locks also may fulfil several functions: locking of ships, taking or discharging water, dividing salt and fresh water, and so on. Bank protection works along a canal fulfil the functions of retaining soil, preventing erosion and guiding ships. Fender walls have a passive function to protect structures etc. Note that most of the functions are permanent and active, but some are passive and just active on demand.

2.3 *Causes of functional losses*

Generally three main causes of functional losses may be distinghuished:

– The technical cause (aging).
Aging of components may result in a sudden or gradual decrease of strength. This may lead to a reduced presentability, to less serviceability or even to a complete loss of function. Depending on the ability of the structural system to cope with these changes, this may result in a loss of function for the whole structure. In addition to the reduction of the strenght, the loads on the structure may increase: a good example is the increase of traffic loads on bridges.

– External causes (expected and unexpected).
Examples of external failure causes are: pollution, fouling, collisions by vehicles, ships or airplanes, strokes of lightning, earthquakes, vandalism, terrorism, etc. Depending on the occurrence frequency and the importance of the structure some of these external causes will have to be taken into account in the design. Some "excess load" will then be included as extreme load.

– Human causes (errors and actions).
Human errors may occur at all stages in the life of a structure:

– the design	(e.g. faulty schematization)
– the execution	(e.g. insufficient concrete cover)
– the use	(e.g. too heavy transport)
– the operation	(e.g. daily emergency stops)
– the management	(e.g. too much deicing salt)
– the maintenance	(e.g. undiscovered defects)

It will be clear that even a conscientious inspection of an aging structure can never guarantee that no loss of function occurs due to the above-mentioned causes. Inspection is then useful, sometimes to detect an unnoticed loss of function, or to limit time-dependent consequences.

Based on empirical data it must be concluded that the contributions made by these three causes to a total loss of function (e.g. expressed in a percentage of time) are of the same magnitude [1], [2]. This puts the benefits of maintenance in its real perspective, but does not relieve the obligation to carry out maintenance: lack of maintenance is always to be blamed.

2.4 *The consequences of functional losses*

Possible loss of production should play an important role in maintenance decisions. One could state that without short or long-term "loss of production", there is no hard necessity for maintenance other than esthetics. In a manufacturing company the consequences of a loss of function of a machine in a production line will be immediately clear in terms of unproduced units. In a similar way, for an infrastructural structures, the product might for instance be described as "accessibility". The the consequential loss in case of failure can then be expressed as waiting time, extra sailing time, time spent on making a detour, etc. It is possible to quantify these losses [3]. This becomes even more clear when no or insufficient production leads to a direct loss of (toll) income.

If a structure "produces" safety, as for example in the case of a water-retaining wall, then the consequences of a loss of function can be divided into (expected) material and immaterial consequences. Material loss in the case of flooding depending on the use of the land amounts to between 10,000 to 10 million guilders per hectare [4], [5]. Although immaterial loss can, by definition, not be quantified, the "economic value" of a victim is estimated as his potential contribution to the gross national product (about one million guilders). Losses suffered by injured people are frequently ignored.

With the ship-guiding, water-discharging, soil-retaining and other functions it is often more difficult to determine the economic value after a loss of function, since the consequential loss caused is more diffuse and occurs gradually. But also in those cases it is useful to make an estimate, since if no consequential losses are known, any maintenance will be considered as uneconomic.

In addition to the above-mentioned observations the following can be said:

- Unlike the situation in a production company, costs and benefits of the infrastructure are not related to one party, but to the government and to the society.
- There is a difference between the products "accessibility" and "safety", namely the probability aspect. Tailbacks due to breakdowns are a frequent phenomenon, while the probability of the loss of human life due to insufficient safety is very small.

2.5 *The types of components in a structure*

In a structure three types of components can be distinguished:

1. The fixed civil engineering components.
2. The moving mechanical components.
3. The electrical or electronic components.

The civil engineering parts are frequently of a static nature and can further be subdivided into concrete, steel, wooden and brick components, rubber and plastic parts and loose granular materials such as sand, quarry run, etc. According to their function they can be supporting, retaining, sealing, protecting, etc.

The mechanical parts are, by definition, moving parts, which can according to their function be subdivided into driving systems and locking systems, further to be subdivided in (electro) mechanical and hydraulic systems.

The electrical components are subdivided according to function into lighting, power supply, driving, steering, monitoring and information systems.

In summary:

Category main parts	*Function(s)*
Civil engineering	supporting / force transmission
	providing connections
	bearing (sliding and hinging)
	soil-retaining / water-retaining
	conducting
	sealing / protection
Mechanical	driving
	locking
	possibility of rotation
	possibility of translation
Electrical / electronic	power supply
	lighting
	driving
	control
	monitoring
	information system

2.6 *Aging behaviour of the different types*

Although in principle all three types of components are subject to aging, the way in which this is expressed is different.

Civil engineering components frequently have one or two dominant aging mechanisms. Since, however, each component is virtually unique as regards design, loads and boundary conditions, it can only be determined by means of inspections whether aging indeed occurs and, if so, what the condition is. Visual inspections result in a qualitative standard by means of the observed damage, while measurements of the so-called condition parameters give a more quantitative impression. Examples of these aging mechanisms are carbonation or chloride penetration into concrete, corrosion of steel sheet piles, fatigue of steel structures, etc.

Mechanical components or systems have a limited number of aging mechanisms (mainly wear and fatigue). Since they are often more mass-produced parts, there is on the one hand more (statistical) knowledge about the future aging behaviour, but on the other hand the complexity and the closedness of such mechanical components frequently makes them inaccessible for direct inspection. Information about the condition is mainly gathered by indirect inspections (condition control).

Electrical and electronic components also have a limited number of aging mechanisms. Since these components are purely mass-produced the knowledge of the future behaviour of the controlled products is great. The use of the inspection is, on the contrary, limited, because of economic considerations, but also because the high speed of degradation. The approach with respect to maintenance is therefore even more aimed at the predicted minimum life of the component. The possibility of inspecting individual components indirectly by means of for instance infra-red thermography can be used for special situations.

In conclusion one can say that going from civil engineering via mechanical to electrical parts, the predictability of the ageing behaviour of components (as a group) increases in terms of lifetime with regard to the fulfilmemt of the function, but on the other hand the measurability of the ageing decreases for each individual component.These differences will also be of importance in making maintenance models.

3 Present practice in maintenance of civil engineering works

3.1 *General*

Maintenance of infrastructural structures in present practice is often a combination of simple inspection techniques in combination with maintenance strategies, which have mainly been developed in practice and are not supported by theory. It roughly incorporates:

Cleaning of visible parts or parts which are liable to break down.
Cursory inspections with a frequency of few times a year of the functioning of the structure, in combination with some preventative small maintenance in the form of the greasing and adjusting of mechanical components or the touching up of the preservative or concrete cover in places.
Technical inspections (every few years), of the technical condition of the structure, if necessary followed by major repairs.
Alarm surveillance service which reacts to failures resulting from exceptional loads, human error or long-overdue maintenance.

In the design stage, the durability and maintenance aspects are often not dealt with in a very explicit way. The designer generally claims the design to be durable and almost maintenance free during its design life. No expectation of the life cylcle costs, including inspection, maintenance and demolition is being made. Instructions to the local manager who is responsible for the structure during its operation are relatively lowlevel or nonexistent at all.

The manager only carries out the traditional periodic visual inspection of all parts. In principle, if damage or is observed, the structure is restored to its original as-new condition (if possible). In this system, the manager only determines time intervals for inspection and maintenance. The lack of a well defined minimum quality level which is to be maintained, forces the manager to aim at an upper limit (the as-new situation), which is often not necessary from a functional point of view and cannot be achieved from a technical and budgetary point of view. However, in spite of the high aim, this strategy may also lead to unsafe situations.

3.2 *Concrete structures*

Concrete structures in The Netherlands have only been applied on a large scale after the second World War, and usually require little maintenance. It is the exceptions, which through bad detailing in the design, the wrong selection of materials, defective execution or improper management cause damage. The most common damage is cracking and corrosion of the reïnforcement. This is mostly detected by the observation of unacceptable cracks or even chunks that have been separated from the cover. A further investigation in the form of a special inspection will then reveal what the (exact) cause of the phenomenon is.

Of course, the aging mechanism could have been discovered at an earlier stage by more advanced methods, like measuring potential differences, settlement and sagging, density and thickness of the concrete cover, depth of carbonation and chloride penetration.

A concrete structure usually has so much robustness and the degradation process is mostly so slow that the visual observation of the first damage gives enough warning to take measures in time, so that a loss of function is prevented. Whether this strategy is cost-effective must still be investigated.

De Sitter [6] has indicated in his "law of five" that one guilder spent on durability during the design stage, is equivalent to five guilders spent for preventative maintenance later, which in turn is cheaper than twenty-five guilders spent on corrective work. Vrouwenvelder et al. [7] have attempted to give this qualitative rule of thumb a quantitative basis by means of models. Some comments, however, must be made on this "law of five".

- It is clear that the costs to guarantee the durability of a concrete structure increase sharply as the aging process progresses. These costs, however, are also incurred later on; so when they are "converted into cash" at the moment of the decision, the difference is much less than a "factor five" (see Fig. 3).
- To be able to carry out the preventative maintenance of an existing concrete structure, it must be known which individual structure from the total stock is a potential "degradation candidate". However this structure will have to be traced through a large number of inspections concerning the total stock.

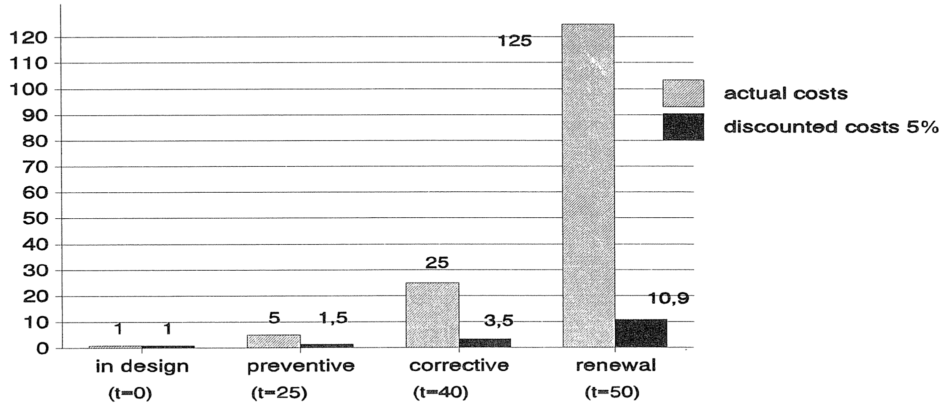

Fig. 3. The "law of five" converted into cash.

3.3 *Steel structures*

For steel structures a distinction must be made between structures with and without a protective coating (zinc and/or preserving agent).

- *Sheetpile structures* are usually not preserved, but are sometimes provided with a once-only layer of coal tar before they are put into place. After a number of years these sheetpile walls can be considered as unprotected steel structures, which have been affected by corrosion to a greater or smaller extent. In a wet or corrosive environment corrosion rates have been measured of 0.5 mm/year in sheet thicknesses ranging between 4 and 20 mm.

  Maintenance of these sheetpile structures is usually limited to periodic visual inspections. When the first defects in the form of soil losses or leaks become visible, the decision is taken to replace the whole sheetpile wall in due course. From [8] it appears, however, that more preventative maintenance strategies, including preservation and/or cathodic protection, could be considered in a number of situations (especially with a corrosive environment), high replacement costs and serious consequences).

- *Bridge and lock gate structures* are usually preserved, with specific multi-layer coating systems (250 to 500 micrometres thick). Due to environmental factors the coating system will gradually age, which first manifests itself by chalking of the top coat and finally by separation of the coating system due to rusting from underneath. Damage and errors in the design or execution can accelerate this process. After this protective coating has eroded, a second stage in the deterioration process begins: the corrosion of the steel structure, which fulfils the actual bearing function.

Until recently, maintenance of these preserved steel structures was based on a replacement cycle of the total coating system of 15 to 20 years, with one or two intermediate inspections to repair local damage. A periodic visual inspection of the coating system aimed at paint defects makes adequate action possible to prevent serious corrosion of the underlying steel structure.

Owing to the new environmental legislation in the Netherlands, including the Pollution of Surface Waters Act, it is no longer permitted to introduce polluting substances into the environment. The removal of coating systems by means of gritblasting has become much more expensive due to requirements with respect to collection and disposal of paint residues (up to NLG 1000/m^2).

The current maintenance strategy for preserved steel structures has therefore to be changed. First of all, the blasting of the structure will have to be postponed as long as possible, by painting the top coat before corrosion has affected the paint system. The intermediate maintenance should include the entire structure and should be carried out more frequently, aiming for a postponement of the complete painting system replacement. A second aim is to limit the preserved surface area, by placing stiffening material on the interior of hollow structures and to condition the climatic condition. An approach that goes even further is using stainless corten steel. Maintenance strategies requiring (little) maintenance should be (re)considered now in the light of high rising painting costs.

3.4 *Wooden structures*

Wooden structures or components have been used successfully for centuries in infrastructural structures, especially in the form of foundation piles, lock gates, lock floors, revetment walls along canals, fender walls, jetties, etc. As with steel and concrete, moisture and oxygen are both necessary to start decay (woodrot). For parts which are permanently under water, therefore, little or no maintenance is required. Also parts which are permanently dry require only limited maintenance. Problems, on the other hand, are caused by wooden structures which are alternately wet and dry, for instance lock gates, revetments walls and fender walls, and structures which are in the tidal zone and/or in the so-called splash zone.

Maintenance of this type of wooden structure consists mainly of visual inspections and replacement in the case of unacceptable weakening. Wooden lock gates with a life of 25 to 50 years are therefore regularly (in the order of every 10 to 20 years) lifted above the water by means of a derrick. Divers are also used, but it is difficult for them to assess the degree of decay visually. It is then better to use so-called penetration meters, plug-drilling methods or taking samples [9].

3.5 *Mechanical components*

Maintenance of mechanical parts is usually carried out according to factory instructions which depend on the use or time, but which are however not tailor-made to the situation. Therefore, especially for larger installations, also indirect condition measurements are carried out, e.g. lubricating oil analyses, vibration measurements, fatigue indicators, etc. In these situations condition-dependent maintenance becomes possible. Adapting the maintenance concept to some specific situation, however, requires extensive expertise with respect to the mechanical system.

3.6 *Electrical and electronic components*

Usually only preventative maintenance is carried out on electrical systems in the form of replacement, based on usage-technical aging or if components are no longer available. For some components corrective maintenance is applied. Sometimes periodic inspections are performed, but these are primarily intended to trace the conditions which could lead to a failure, e.g. contacts which have become loosened by vibration or moisture in a distribution box.
A more condition-dependent form of maintenance is performed sometimes in the form of infrared tracing of hot (and therefore critical) switches (e.g. contacts affected by burning, a break in the wiring). The problem is that at the moment of inspection the switches must be electrified.

Electronic components are increasingly provided with a self-test and if necessary each module can be replaced. This means that the operational reliability during use is an integrated part of the design.

3.7 *Soil and other loose-granular structures*

Infrastructural structures often contain parts consisting of loose-granular materials, such as sand, gravel, rubble stone, etc. whether or not covered with a protective layer of clay, grass, foil, cloth, asphalt, stone pitching, etc. The aging processes in these cases concern uneven settlements or damage to the covering layers, so that the loose-granular material can be eroded. Often there is a so-called two-tier system, which enables maintenance of visually observed damage to be carried out on time, that is before loss of function occurs.

4 Civil engineering maintenance concept

4.1 *Definitions*

Some definitions of maintenance will be discussed:

> "Maintenance is keeping things in a good condition"

This short dictionary definition appeals to the common sense of what maintenance in general is meant to be.

> "Maintenance is keeping components in a good condition so that the structure can fulfil its functions"

For years this has been the simple but rather vague maintenance concept of operational managers, giving a large degree of freedom for individual interpretation. Which components? How good? Which functions? How reliable?

The implicit philosofy behind this concept is the statement that if all components are in a nearly-new-condition, the structure will fulfil all the functions ever intended by the designer on an acceptable level. In fact, it relieves the manager of thinking it all over again. Yet physical and financial limits lead to the opinion that this approach is no longer feasible and more sophisticated maintenance concepts are desired.

> "A maintenance concept is the total of technical activities on the component level, geared to each other and economicaly balanced, in order to keep or to get the structure in such a condition that it can fulfil its function(s) for a certain period with sufficient reliability, availability, serviceability, durability and presentability."

For such an approach practical experience and good housekeeping only are no longer enough. One has to consider the essenctial features of structural design and maintenance, in particular:

- The aims of management and maintenance;
- The functions and demands of the structure;
- The functional relationship between structure and components;
- The type of ageing mechanisms on the component level;
- Cost of inspection, maintenance and consequences of failure;
- Maintenance strategies and actions to intervene;
- Desicion methods to support the choice of right actions;

There seems to be a need to give some guidance in this field.

4.2 *Targets*

The above-mentioned maintenance concept makes it clear that maintenance activities ought to have explicit targets based on the function of the structure within the total infrastructure. As maintenance-targets for the structure's functional behaviour may be distinguished:

- reliability, which is the likelyhood that a structure or component can fulfil its functions during a given period.
- availability, which is the percentage of time (or times) that a structure or component is available to fulfil its functions.
- serviceability, which is the measure in which the object is suitable for use.
- durability, which is the ability of the object to fulfil its functions during a certain period of time.
- presentability, which is the fitness to be shown in public.

A target for the management organisation can be considered to be:

- An economic cost optimum, taking into account all (expected) costs for a certain period of time.

Notice that the required degree of reliability etc. may follow from an internal economic balance (see last target), from an external given demand, or from a historical based and socially accepted level. Notice that 'a certain period' may vary from the next inspection-interval up to the lifetime of the structure. In which the lifetime may follow from an economic, technical or social consideration.

4.3 *General approach*

A rational approach to maintenance can be presented by the next steps [10], [11]:

1. Specification of the (current) function(s) of the structure and the components
2. Definition of the associated maintenance targets.
3. Definition of the relations between basic events (component failure) and the top event (loss of function). A basic event, defined as mal-functioning at the component-level, may arise from three origins: human influence (errors, intervention), external causes (collission, burning, etc.) or technical reasons (aging-mechanisms, overloading). The consequences of the top-events may be found by social-economical and/or business-economical considerations.
4. Definition of an individual maintenance rule; for dominant components such a rule should be based on quantitave maintenance models as far as possible.
5. Tuning of maintenance actions: in order to save costs, to have less "production-losses" or because of budget or capacity restrictions, there may be a need for combining or spreading the individual maintenance actions.

4.4 *The basic maintenance strategies*

On the component level there may be three maintenance strategies:

1. *Failure-based maintenance (FBM):* maintenance actions are undertaken after failure has been noticed.
2. *Use-based maintenance (UBM):* maintenance actions are taken after a certain use (time, distance, load history, etc.).
3. *Condition-based maintenance (CBM):* maintenance actions are taken after a certain (unacceptable) condition limit is exceeded and noticed (by inspection, monitoring, performance, fuel and oil consumption, etc.).

In the case of inspection, a further distinction can be made between use-based inspection intervals and condition-based inspection intervals.

The FMB maintenance strategy is applicable to all parts or components, but will always lead to corrective maintenance and certain consequences of failure. The UBM strategy is useful, if a relationship is known between failure and use, and so may lead to preventive maintenance. The third strategy is only applicable, if the condition is measurable, and so may lead to preventive maintenance.

In practice these basic strategies for civil engineering structures are not so clearly separated:

- Many parts do not show "binairy" failure-behaviour. Slight damage or lower performance give warnings before failure, so there is a possibility to change failure based into condition based maintenance.
- Structures with parallel arranged components often have some redundancy. So failure-based maintenance on the component level may be seen as condition-based maintenance at a higher level.
- Indications of an inadequate condition combined with a global indication about use may lead to preventive maintenance.
- Budget restrictions often dominate the maintenacne decisions; as a result preventive maintenance may change into corrective maintenance.
- Sometimes external reasons dictate the actual moment of action.

4.5 *Types of degradation processes*

Components of civil engineering structures fail or lose their function, if the strength of that component is no longer high enough to carry the actual load. The way in which the strength decreases with time is called the aging or degradation process. Some examples will be discussed (see Fig. 4):

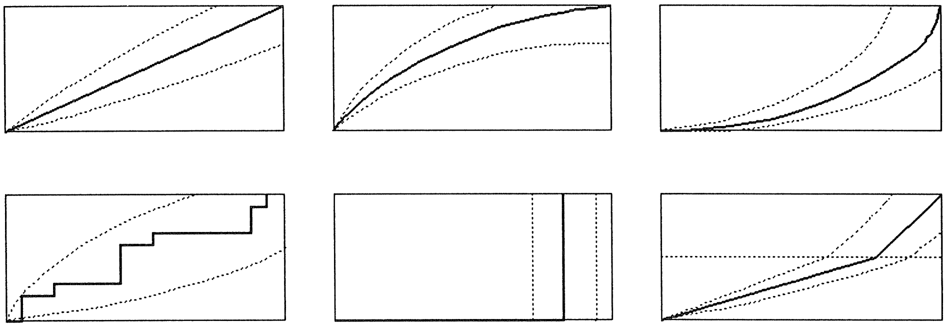

Fig. 4. Possible courses of degradation.

- The simplest example is a degradation process which is lineair in time and has an uncertainty that may increase e.g. with the square root of time. In many cases the corrosion proces over years or the wear-and-tear process can be represented in this way (Gaussion process).
- The degradation process may also slow down, for example in processes like carbonatation or chloride penetration in concrete. Mathematically these processes could be described by square root or error functions
- When degradation accelerates in time, e.g. following an exponential curve, the aging process may be associated with fatigue or the loss of cover stones on a slope. Notice that degradation is caused by cumulative load effects but that failure is normally caused by an extreme load.
- In cases like collisions, degradation is mainly caused by extreme loads and the degradation process is no longer continuous in time but step wise.
- In the extreme case no degradation at all but only a sudden load causes failure. It should be clear that in such a case inspection is meaningless and that this failure behaviour requires a different maintenance approach.
- Many civil engineering components are designed in such a way that they have a so-called two-stage-mechanism. In the first stage degradation of a protection layer takes place and in the second the real structural part is attacked. Examples of such protection layers are the concrete cover on the reinforcement, the coating on a steel structure and the cover stones on the slope of a dyke.

The type of aging mechanism is of great importance for the choice of the maintenance strategy. A two-stage mechanism has the advantage of a simple and timely warning. The damage during the first stage may be considered as a condition parameter of the second stage. For a one-stage mechanism the course of degradation is much more important.

Since degradation is often progressive, a fatal deterioration development may easily slip through between two inspections.

4.6 *The structure as a technical system (components and functions)*

A civil engineering structure such as viaduct or a sluice consists of many components, working together in structural and functional hierarchy. At the top of the technical system one or more functions have to be fulfilled and at the base components may lose their function by human errors, external causes or degradation. Though in principle maintenance takes place at the component level, the type of maintenance strategy does not only depent on component characteristics but also on the consequences at the system level (structure or even infrastructure).

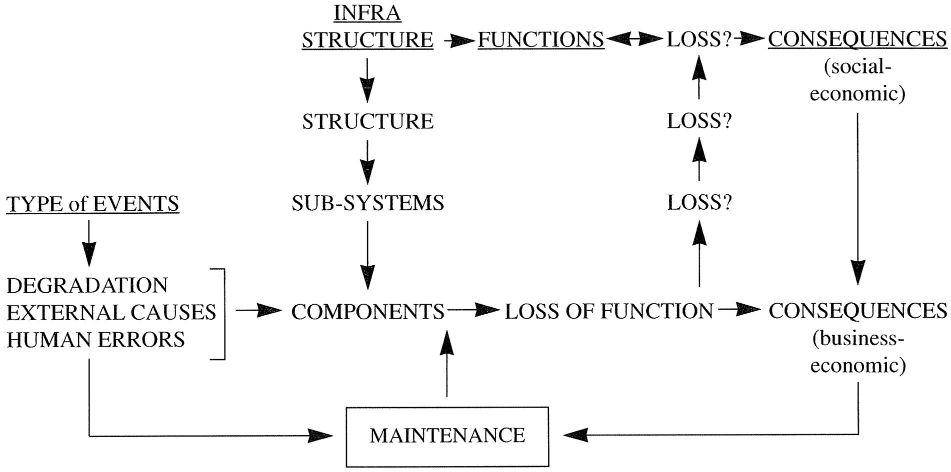

Fig. 5. Events at the base and their (possible) consequences.

4.7 *Decomposition into parts and consequences of failure*

For each function at the structural level one should make a system decomposition up to the level of maintainable components or sub-systems. If the structure is simple, the cause and consequences of component failure will be clear. However if the structure is complex, this decomposition has to be followed by system analysis for example by an FMEA (Failure Mode and Effect Analysis). The analysis should give insight into the system behaviour (the relation between basic events and top events). Together with the different consequencies of loss (business- and/or social-economic), the consequences of the component under consideration can be determined (see Fig. 5).

4.8 *Qualitatively based maintenance rules*

Given the failure consequences of a single component, the primairy maintenance rule for this component may be established in an isolated way. This rule should be based on failure consequences and on information about cost of possible maintenance actions such as inspection and repair or replacement.

Another important ingredient is the components behaviour in time.
The loss of strength may be a steadily continuing well-known or easily measurable process and the associated load a nearly stationary one (e.g. corrosion of sheetpilings). Sometimes there is no knowledge about strength and loads but only collected data on the level of the component's behaviour in terms of a probability function of lifetime (e.g. electro-mechanical components).

In practice there is always too little or only global knowledge about costs and behaviour, enabling only a qualitative decision about the best maintenance rule. At a preliminary stage of the maintenance planning this is not a too serious problem: this stage should mainly be seen as a preselection. Only the dominant (costly, sensible or vital) components will require better data at a latter stage. A qualitative selection of maintenance rules can be formulated as indicated in figure 6. Notice that this qualitative decision-tree is based purely on an economic approach. Externally given (safety) requirements may overrule such a maintenance concept.

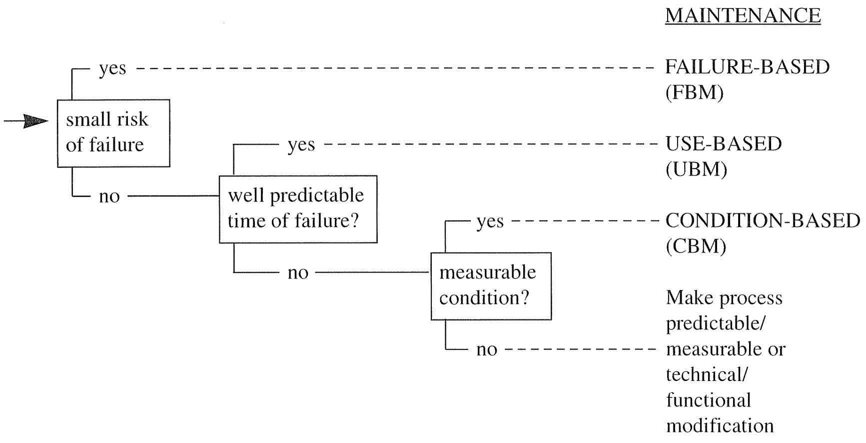

Fig. 6. A qualitative decision-tree for maintenance strategies.

Notice that in all three strategies the repair costs will occur anyway, so the choice is mainly based on the extra cost.

Risk is defined as the product of two contributions: failure consequence and failure probability. When in the case of aging, the failure rate increases with time, the "small risk" may grow and the failure-based maintenance may transfer into one of the preventive strategies. So a 'small risk' is related to the time period in question.

An "easily predictable time of failure" means that there should not be too much spread in this lifetime. Otherwise the cost of lost residual lifetime is too high in comparison with the cost of inspection.

A 'measurable condition' may imply a directly measurable conditional parameter like thickness, an indirect measure like full-consumption or even the amount of visible damage. It should be clear that here the costs of inspection play an important role.

Qualitatively based maintenance rules at the component or sub-system level will give a initial insight into vital components with high failure consequences, in sensible components with a short lifetime, in unknown components with high probability of failure, in costly components with high repair, replacement or inspection costs etc.
These dominant components will mainly dictate the maintenance concept, while other components are consequential and do not require further effort.

4.9 *Quantitatively based maintenance rules*

As seen above the qualitative approach balances three types of cost: risk, repair (or replacement) and inspection. Not in an absolute sense but because the target is minimum life cycle costs, they should be balanced on a time-basis. The longer the component will fulfil its function, the lower the costs per unit of time are, but the higher the risk of failure may be or the more inspections are needed to lower that risc. As most components of a civil engineering structure have a relative long lifetime, the real interest rate plays a roll too.

For the various maintenance types the following cost expectations per time unit can be given:

Failure-based: $$E(c) = \frac{C_\mathrm{r} + C_\mathrm{f}}{T_\mathrm{c}} \qquad (1)$$

Use-based: $$E(c) = \frac{C_\mathrm{r} + P_\mathrm{f}(t_\mathrm{r}) \cdot C_\mathrm{f}}{T_\mathrm{c}} \qquad (2)$$

Condition-based: $$E(c) = \frac{C_\mathrm{r} + n \cdot C_\mathrm{i} + P_\mathrm{f}(n, g) \cdot C_\mathrm{f}}{T_\mathrm{c}} \qquad (3)$$

in which: E(c) = Expected total cost per unit of time
C_r = Cost of repair or replacement
C_i = Cost of inspection
C_f = Cost of failure
P_f = Probability of failure
T_c = Mean lifetime
n = Number of inspections
g = Boundery of rejection

Fig. 7. Simplified cost formulas of maintenance strategies [12].

The cost of failure-based maintenance is given by the cost of repair (or replacement) plus the total cost of consequencies of failure, divided by the expected (average) lifetime.

The cost of use-based maintenance is given by the cost of repair (or replacement) plus the risk of failure up to the time when action is taken, divided by the expected lifetime, which is nearly the cycle of the planned repair.

The cost of condition-based maintenance is the most complex one, because not only the inspection intervals but also the level of rejection influence the expected lifetime and the remaining risk.
Failure or rejection in their turn influence the number of inspections. So the total cost is given by the cost of repair (or replacement), the expected inspection costs plus the total risk of failure and divided by the expected lifetime.

Notice that failure-based maintenance may not be influenced by the maintenance manager other than by limiting failure consequencies. The use-based maintenance has one influence possibility (time of repair action) and the condition-based maintenance has two possibilities to steer (inspection times and rejection level).

There are a few dutch computer programs on an analytical e.g. KMOSS-KEMA or markovian basis e.g. OPTIMON-FEL/TNO, that for a given probabilistic degradation process plus failure boundary and the three cost contributions will automatically find the cost-optimal strategy or the cost of a given strategy .

4.10 *Maintenance of the system*

The quantitative maintenance rules for the dominant components and qualitative rules for the others need to be combined to one geared maintenance concept for the structure as a whole.

A first tuning combines maintenance actions (inspection and/or repair) resulting in lower overall costs. In this case the economic advantage of mobilization, adjustment and scale should compensate the loss of optimal individual strategies. For example lifting the door of a sluice by means of a crane vessel is often so costly that repair actions carried out on the door, the hinges or even the whole sluice will be combined.

The second tuning combines maintenance actions (inspection and/or repair) resulting in a shorter out of use time. In this case the economic advantage of a higher availability (social profit) should be compared with the loss of optimal individual strategies.

The third tuning combines maintenance actions resulting in inspection and repair planning which is more workable from an organisational point of view. A use-based maintenance strategy, having all maintenance activities into a predictable scheme, is sometimes preferred to the uncertain failure-based or condition-based strategies. Budget or capacity restrictions may further lead to a smoothing of maintenance activities, resulting in a more or less constant annual volume. In addition, there may be many external motives for choosing alternative options: maintenance of an old bridge may have to wait for a new parallel bridge to be finished or traffic signal supports may have to be inspected every five years according to some legal rules.

5 Implementation of theory in practice

From the previous chapters it will be clear that there is a gap between maintenance theory and current practice in civil engineering. An attempt is made here to bridge this gap. In this chapter the steps 1 to 5 as defined in 4.3 will be applied to a viaduct and a sluice.

5.1 *Example 1: a reinforced and prestressed concrete viaduct*

Step 1: Definition of the main function(s)
The function of a viduct might be formulated as: the crossing for traffic at one level over traffic at another level. In some cases there may alos be secondary functions like the crossing for electricity- or telecom-cables, sewer pipes. The main function can further be defined by specifying traffic class, traffic intensity, number of lanes, design life, etc. From there technical entities like traffic loads, width, heigth, etc. can be derived, which together with financial, environmental and legal conditions determine the design.

A maintenance-minded designer will include a maintenance concept in the design and seek for minimum total lifecycle costs. If not, in a latter stage the maintenance manager has to do this job. However, after construction of the viaduct there is less freedom to take optimal measures. On the other hand for an existing structure there may be much more data available than there is in the design stage.

Step 2: Definition of the maintenance targets.
The mission of the designer or manager is to make a maintenance concept for the viaduct in such a way that it fulfils its intended or current function(s) with sufficient reliability, availability, serviceability, durability and presentability during the considered periode (e.g. expected lifetime) and for minimum integral costs.

- The target “sufficient reliability” could be read as: all components should be in agreement with design-codes. This means however that if the structure has no overstrength at all, no constructional damage whatsoever can be tolerated. Fortunately, the management stage is a new situation with other cost rates and with a lower (economical determined) reliability level [13],[14]. In this viaduct example, the prefabricated and prestressed concrete girders in combination with the deck are of main interest with respect to safety against failure. Although tolerable, it is questioned here whther a lower safety level can actually be spotted in practice (economics).

- Sufficient availability is a target that must be economically determined on a higher (infrastructural) level. Traffic intensity and alternative routes play an important role. The extra costs of preventive versus corrective measures should be balanced against the risc of delay or deversion. A study of McKinsey gave a cost of 25 NLG per car per waiting hour [3]. Let us assume that the example viaduct is assumed to have low traffic intensity (less then 10.000 vehicles per day) and there are no movable parts. Non-availability with technical origin comes mainly from inspection and repair-actions itself. For example a broken roadway expansion joint may give an unforeseen extra delay of one hour. This will cost about 25*10.000/24=10.000 NLG; so availability is expected not to play an important role in this case.

- Sufficient serviceability is mainly influenced by the quality of components like roadway expansion joints, asfalt layers, waterdrains, electric lighting and by deformation or settlement of the structure. Here it is very difficult to make an economic balance between costs of preventive maintenance actions and the drivers risc consequences of a lower service level. Quantitative attempts have been made e.g. for asphalt-unequalty versus risc of accidents with outcome that rut depth should be less then 18 mm. Allthough there will be similar vague relations for the level of illumination, deformation etc., a practicable way here is to establish first a qualitative and empirically based agreement about what is tolerable.

- Sufficient durability is especially of interest for those components that influence the reliability in the long run. Examples are the concrete cover layer on reinforcement, galvanized and coating layers on steel structures and neopreen layer of rubber bearings. A substantial part of the common maintenance effort is focussed on durability. In many cases it can be proven that this preventive maintenance actions payes off [7]. On component level durability demands may be formulated in terms of for example a tolarable chloride concentration in the concrete cover, a maximum corrosion percentage for coated or galvanized steel components, etc.

- Sufficient presentability is the softest of all targets and will easily be sacrificed in cases of budget shortage. However, in the case considered here the viaduct is not painted and the concrete surface itself is expected to present well for the decades to come.

- The design lifetime for a viaduct is generally 50 year but the real lifetime might be completely different. This influences the maintenance concept in such a way that all decisions are based on the idea that the viaduct is a permanent provision. Although the lifecycle of the viaduct is not known, the target minimum lifecycle costs is still relevant as costs to be made in the far future are fading out because of the interest-effect. In the Netherlands the discount rate for this kind of maintenance dicision is fixed administratively in 1986 on a 5%-level.

Step 3: Relations between basic events and top events.
The third step is to find the relations between the possible basic events, the probable loss of function and associated business- and social-economical consequences. Therefore the 'viaduct' as technical system has to be subdivided into maintainable subsystems or parts:

Table 1. Components of the viaduct.

1	<u>THE MAIN BEARING STRUCTURE</u>	2	<u>THE SUPPORTING STRUCTURES</u>
1.1	THE PREFAB CONCRETE BEAMS	2.1	TWO ABUTMENTS
1.1.1	The structural concrete	2.1.1	The foundation slabs
1.1.2	The reinforcement	2.1.2	The foundation piles
1.1.3	The prestressed cabels	2.1.3	The rubber bearings
1.1.4	The concrete cover	2.1.4	Roadway expansion joints
1.2	THE IN-SITU CAST DECK	2.1.5	The traffic impact slabs
1.2.1	The structural concrete	2.1.6	Soil retaining structures
1.2.2	The cross reinforcement	2.2	ONE INTERMEDIATE PIER
1.2.3	The concrete cover	2.2.1	The rubber bearings
1.2.4	The asphalt layer	2.2.2	The column head
1.2.5	The crash barriers	2.2.3	The column
1.2.6	The parapets	2.2.4	The foundation slab
1.2.7	The water drains	2.2.5	The foundation piles
1.2.8	The electric lighting		

After the decomposition a systems analysis should make clear which events at the component level are reponsible for which loss of function at the top (structural level). This way the consequences of component failures become evident. As a viaduct is a simple system this may be done without the help of a formal system analysis.

As stated before, basic events may have three different origins:
1. Human influence like errors in design, construction, use, etc.
2. External causes like accidents, fire, lightning, earthquake, etc.
3. Technical causes especially degradation mechanisms like chloride penetration, corrosion, etc.

The first kind of event is partly covered by design checks, quality control during construction, by inspection during the first five to ten years, by well written manuals, etc. For the second kind of event preventive measures may be taken to limit consequences but the residual risc has to be taken and maintenance is only corrective. The third kind of event is of our main interest, as preventive maintenance may have influence.

Some technical degradation processes will be discussed:

- Chloride-penetration in concrete parts (from deicing salt) may be followed by pitting corrosion of reinforcement or prestressed cables. This process is generally not detectable by visual inspection and may lead to a sudden failure. Prefabricated concrete beams however are normally of excellent quality, so if chloride is not mixed in advance and the real cover is more than 20 mm [18], this mechanism is only possible for in-situ cast concrete. Note that in fact not chlorided concrete but corrosion of steel is the weak link. For the concrete components no other mechanisms for inside or surface attack are expected at this location.

- Asfalt-layers are suffering from wear and tear in a rather good predictable and measurable way. When the rut depth grows, the drivers comfort will decrease. Especially when it rains this will finally lead to unsafe situations. The expected (service) lifetime is in the order of 20 years, depending of the chosen criterion.

- The crash barriers are galvenized, so corrosion only will start after 10 to 15 years. Without intervention this will finally (e.g. after 25 years) lead to an unsafe 'stand-by' component.

- The parapets are painted steel components that only suffer from corrosion after degradation of the coating. If preventive maintenance actions (every 8-10 years) are not in time this will finally lead to an unsafe 'stand-by' component.

- The water drains may be polluted after a certain period, depending of location and season. If not cleaned rather frequently (1 to 4 times per year), this will lead to drivers objections and so to less serviceability.

- The electric lighting has on the one hand a limited but easily predictable life time (e.g. 10.000 burning hours). On the other hand less intensity of illumination will gradually lower the serviceability.

- Broken foundation-piles or a cracked foundation slab may suffer from corrosive groundwater. This may lead to local damage, but because of redundancy and warning seldom to failure.

- The foundation may suffer from (unequal) settlements and the deck and beams may suffer from time dependend deformation (creep). Both effects are gradual processes and may lead to less serviceability. To some extent, however, the effects can be corrected by adjusting the thickness of the asphalt layer.

- The rubber bearings sometimes becoming cracked by UV-light and overloading caused by horizontal displacement of the abutments. Crackes may be followed by corrosion of the inside steel plates.
  If this reinforcement is out of action, shear forces may grow and so may cause local damage to the concrete structure. The characteristics of this process is highly uncertain.

- The roadway expansion joints suffer mainly from wear and tear caused by the dynamic traffic load and has wide spread in expected lifetime (e.g. 10–30 years). The consequences of mal-functioning are less comfort to the driver, damage to tires and will finally lead to accelerated damage of the structure itself and unexpected delay.

- The impact slabs may slowly settle in time caused by traffic and settlement of the surrounding ground. Consequences are less comfort. The process depends strongly on the local circumstances.

- The coverstones from the soil-retaining slope may be pulled, pushed or washed out by vandalism, roots or discharge of rainwater. Without inspection and intervention this will first lead to a bad appearance and at the very end to an unsafe situation of the abutment.

Table 2. Components and aging-mechanisms relevant to the targets. Notice that most of the maintenance effort is primarily trickered by serviceability and durability.

Nr.	Component or sub-system	Ageing-mech.	Maint.Targets				
			R	A	S	D	P*
1	MAIN BEARING STRUCTURE						
1.1	PREFAB CONCRETE BEAMS	creep	.	.	1	.	.
1.1.1	structural concrete	chlor. mixed	2	.	.	1	.
1.1.2	reinforcement	chlor.→ corr.	2	.	.	1	.
1.1.3	prestressed cabels	chlor.→ corr.	2	.	.	1	.
1.1.4	concrete cover	chloride pen.	3	.	.	1	2
1.2	IN-SITU CAST DECK						
1.2.1	structural concrete	chloride pen.	2	.	.	1	.
1.2.2	cross reinforcement	chlor. → corr.	2	.	.	1	.
1.2.3	concrete cover	chloride pen.	2	.	.	1	.
1.2.4	asphalt layer	wear and tear	.	.	1	2	.
1.2.5	crash barriers	degalv. → corr.	.	.	2	1	.
1.2.6	parapets	decoat. → corr.	.	.	2	1	3
1.2.7	water drains	pollution	.	.	1	2	3
1.2.8	electric lighting	blowing	.	.	1	.	.
2	SUPPORTING STRUCTURES						
2.1	ABUTMENTS	settlement	3	.	1	2	.
2.1.1	foundation slab	chlor.→ corr.	2	.	.	1	.
2.1.2	foundation piles	cracks → corr.	.	.	1	2	.
2.1.3	rubber bearings	U.V. → corr.	2	.	.	1	.
2.1.4	roadway expansion joints	wear and tear	.	2	1	3	.
2.1.5	traffic impact plates	wear and tear	.	.	1	2	.
2.1.6	soil-retaining structure	erosion	.	.	.	1	2
2.2	INTERMEDIATE PIER	settlement	3	.	1	2	.
2.2.1	rubber bearings	U.V. → corr.	2	.	.	1	.
2.2.2	column head	chlor. → corr.	2	.	.	1	.
2.2.3	column	chlor. → corr.	2	.	.	1	.
2.2.4	foundation slab	chlor. → corr.	2	.	.	1	.
2.2.5	foundation piles	cracks → corr.	.	.	1	2	.

* R = Reliability A = Availability S = Serviceability D = Durability P = Presentability)

Although there are many components as well as aging mechanisms, they may be of interest for the different targets. Table 2 gives indications which components of the viaduct are of primary (1), secondary (2), etc. importance for the five maintenance targets under consideration. Some comments to this table:

* Sufficient reliability
Of all components direct contributing to the maintenance target 'sufficient reliability', the prestress-strands in the prefabricated beams are most sensible to degradation (pitting corrosion after chloride penetration). However the high quality and the thickness of the concrete cover (controled by Q.A. and zero-inspection) makes the occurence of this aging process improbable; furthermore, the amount of wires in a strand, the amount of strands in a beam and the amount of beams in the viaduct makes it unrealistic that such a (multi parallel) system will suddenly fail without any local visual warning. The other concrete components have a lower quality (cast in situ concrete) but the reïnforcement bars are less sensible to brittle fracture. The parallel bars will also have a favourable influence. In concrete parts which are under pressure, reinforcement sometimes may even be missed. This type of viaduct as a mechanical system is rather insensible to settlements. Conclusion: In this type of viaduct 'sufficient reliability' does not seem to be the most important maintenance target.

* Sufficient servicebility
Components like the asfalt layers, crash barriers, electric lighting, expansion joints are mainly important for servicebility of the viaduct. The consequencies of degradation are primarily a reduciton in serviceability, for which cost-consequencies are hard to quantify. For example there is a vague relation between rut-depth and victims per km-year, which forms the basis of a maximum depth of 18 mm. In general these levels are more historically grown and socially accepted than economical proved. Because these service-levels are within the normal maintenance-scope there is a lot of experience about the rate of degradation etc. So inspection-intervals and maintenance actions may easily be related to this experience and the socially accepted limits.

* Sufficient durability
This is in fact a business-economical target, not driven by external failure-consequences: delay of maintenance may lead to extra costs or shorter residual lifetime. For most components a preventive maintenance action like repair of the protection-layer is more economic than repair of both protection system and protected component. The 'Law of five' of de Sitter [6] and the example of the balcony plate [7] proves this in a quantitative way. So for most of the stuctural components 'sufficient durability' seemes to be the driving maintenance target. When degeneration, cost of inspection, maintenance and consequencies (extra repair cost or shorter lifetime) are known, an optimal strategy may be found.

* Sufficient presentability
Because the concrete cover of the beams has a good durable surface, only the maintenance of the parapets, the waterdrain and the soil retaining structure could be influenced

by this target. However maintenance from the target 'sufficient durability' will mainly overrule this. Qualitative maintenance rules for individual components

Step 4: Definition of individual maintenance rules.
In this step a qualitative consideration gives the primairy maintenance rules with the help of figure 6, considering the probability of aging, the probability of system failure, the associated external social or the internal business economics consequences.

Table 3. Qualitative maintenance rules for individual components.

Nr.	Component or sub-system	Rule	(arguments)
1	<u>MAIN BEARING STRUCTURE</u>		
1.1	PREFAB CONCRETE BEAMS	CBM	(concerning deformations)
1.1.1	structural concrete	FBM	(no mechanism)
1.1.2	reïnforcement	FBM	(low risc)
1.1.3	prestressed kabels	FBM	(low risc)
1.1.4	concrete cover	CBM	(risc=extra cost of repair)
1.2	IN SITU CAST DECK		
1.2.1	structural concrete	FBM	(low risc)
1.2.2	cross reïnforcement	FBM	(low risc)
1.2.3	concrete cover	CBM	(risc=extra cost of repair)
1.2.4	asfalt layer	CBM	(risc + easy to measure)
1.2.5	crash barriers	CBM	(risc=extra cost of repair)
1.2.6	parapets	CBM	(risc=extra cost of repair)
1.2.7	waterdrains	UBM	(well predictable)
1.2.8	electric lighting	UBM	(well predictable)
2	<u>SUPPORT CONSTRUCTIONS</u>		
2.1	ABUTMENTS	CBM	(concerning settlements)
2.1.1	foundation slab	FBM	(low risc)
2.1.2	foundation piles	FBM	(low risc)
2.1.3	rubber bearings	CBM	(risc=extra cost of repair)
2.1.4	road expansion joints	CBM	(risc + easy to establish)
2.1.5	traffic impact slabs	CBM	(risc + easy to establish)
2.1.6	soil-retaining structure	CBM	(risc=extra cost of repair)
2.2	INTERMEDIATE PIER	CBM	(i.r.t. settlements)
2.2.1	rubber bearings	CBM	(risc=extra cost of repair)
2.2.2	column-head	CBM	(risc=extra cost of repair)
2.2.3	column	CBM	(risc=extra cost of repair)
2.2.4	foundation slab	FBM	(low risc)
2.2.5	foundation piles	FBM	(low risc)

As a rule of thumb, the final inspection interval of condition-based maintenance may be choosen in the range 0.05 - 0.20 of the meantime between failure (MTBF). For dominant components it may be fruitful to find better proven quantitatively based maintenance rules. Components may be dominant in the sense of costs (inspection, repair or consequences), in the sense of reliability, availability etc. or in the sense of lifetime.

For the components of the viaduct there are only a few condition which can not be determined just by visual inspection but need more costly measurements. These are e.g. the depth and intensity of the chloride penetration and the real position of the reinforcement. If the reinforcement or prestressing is already in the corrosion stage, even more costly inspection technics like potential field measurements or reflectrometry are needed. Chloride penetrated concrete askes also for costly repair methods depending on the actual stage of the degradation proces: Starting with painting, via increasing of the cover layer, up to cathodic protection or even renewing of layer and reinforcement.

Failure of the main bearing structure (beams, deck, columns) may lead to a considerable number of casualties. Systems reliability, however, shows that such an event has a very low probability, given an economical optimal maintenance scheme. Let for example, given the actual environmental conditions and concrete cover, the critical chloride concentration (one percent on cement base) be expected to reach the reinforcement after 25 years on the average with a standard deviation of 5 years. The costly ultimate consequences in that case (renewing of cover layer and attacked reinforcement) are expected to be met and these costs are estimated to be a 1000 Dutch Guilders/m^2. Preventive maintenance action (paint) is still possible if the chloride concentration is less than 0.5%. Up to this level the associated cost are 200 Dutch Guilders/m^2 gradually increasing above 0.5%. Inspection to the concentration of chlorides will cost 10 Dutch guilders/m^2. For this case the computer model OPTIMON [16] gives the next maintenance strategy: Condition Based Maintenance (CBM) with a level of 0.4% chloride on cement base as action limit; inspection intervals have to decrease from 7 to 5, 3 and 1 year when the chloride level found during the inspections increases from zero to 0.4%.

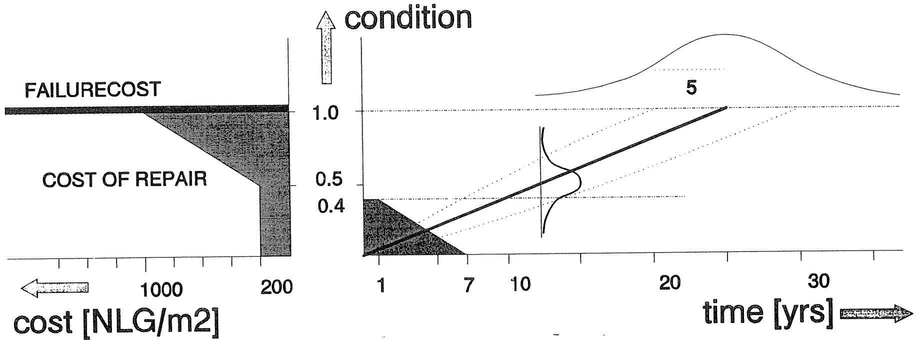

Fig. 8. Course of costs and condition dependend inspection interval.

It is remarkable that even high external consequences of failure (e.g. 1.000.000 Dutch guilders) at the 1% chloride level does not have much influence on the outcome. So the business economical driven strategy is dominant against the social-economic.

A same kind of quantitative analysis may be done for the galvanized crash barriers and the painted parapets. Both will have extra cost of repair if the protection layer is no longer effective, but here the degradation process itself is much better known.

Step 5: Tuning of maintenance actions.
In this step individual maintenance actions may be combined because of savings in maintenance cost, less "production-loss", organisational benefits or budget and capacity restrictions. For example the 7 or 8 years inspection interval for chlorides, crash barriers and parapets may be taken as a basic frequency on which the other condition based strategies e.g. for rubber bearings are tuned to. Similar for settlements and deformations inspections, provided that these inspections are performed by the same inspection team. Given the possible (speed of) degradation, roadway expansion joints need a shorter (e.g. 4 years) interval and may be combined with the inspection of the asphalt layer, impact slabs etc. Waterdrains and electric lighting may be covered by a global inspection (e.g. two times a year). So the final maintenance concept may be rather simple, but well underpinned.

5.2 *Example 2: The sluice*

Step 1: Specification of the functions of the structure.
In general a sluice may have four or sometimes five functions:

1. A barrier of a certain difference in water-level.
2. A sluice for a certain amount of water.
3. A lock through of ships.
4. A traffic crossing over doors or associated bridge.
5. A barrier between salt and fresh water.

Step 2: Definition of the associated maintenance targets.
The first function has primarily to do with the maintenance target sufficient reliability, the second function with sufficient availability and the next two functions with sufficient availability and serviceability and the last one with sufficient serviceability.

Step 3: Decomposition and composition.
A sluice has two main structural elements:

- The lock chamber (heads, doors, walls, bottum) → civil engineering
- The mechanisms of movement (drive, transmission) → elektro-mechanic

A very comprihensive system analysis is given below:
The reliability of the water-retaining function is mainly dominated by the quality of the so called flooddoor(s), while the mechanisms of movement of the doors is here less important because there is often a hand-driven possibility (parallel components).
The availability of the water discharge function is mainly influenced by both double executed sliding gates (parallel components).
The availability of the navigation lock function is dominated by both mechanisms of movement of both doors (serial elements).
Here the hand-driven possibility gives no workable situation.
In some cases the mechanisms of movement of the crossing bridge, the associated traffic barriers, lights and cameras may play a roll too.
The availability of the bridge function is mainly dominated by the mechanism of movement of the bridge (often with a parallel hand-closure procedure), traffic barriers, lights and sometimes cameras.

In headline the maintenance concept of a sluice will be dominated by the reliability of the flooddoors and the availability of the mechanisms of movement of both couple of doors, depending on the consequences on the level of the infrastructure.

Step 4: Definition of maintenance rules.
With the help of OPTIMON the maintenance strategy of the doors may be quantified and with KMOSS the maintenance strategy of the mechanisms of movement may be sustained.

Degradation of the doors may be estimated on the base of experience.
The proces is accepted to be progressive in time (t^2) e.g. 0 → 100% in 25 years(μ) ± 5y (σ). When the safety-margin is spend the cost consequences (1.000.000 NLG) are caused by inundation.
Inspection of the doors takes a 5000 NLG per time and maintenance (here replacement) cost a 100.000 NLG.

The cost-optimal strategy is found to be condition-based maintenance with a cost level of 4868 NLG/year, a mean lifetime of 24 year, a boundery of preventive action at a 75% and a condition based inspection interval starting with 16 years till 2 years for a condition nearby the rejection boundery.

In the case of use-based maintenance the optimal revision interval is found to be 19 year and the level of yearly costs 5734 NLG/yr.
The mechanisms of movement are split up in two main components:
- The driving part (e.g. the hydraulic oil-pump)
- The transmission part (e.g. the hydraulic jacks)

The driving part is characterized by a random failure period of 10 years (T_0) with a constant failure rate of 0.001 per year (Z_0).
After that period degradation starts up which gives the component a mean lifetime of 20 years (T_{gf}).
The fixed cost of maintenance (here replacement) are 20.000 NLG (K_v). The variable costs of unexpected corrective maintenance are given by 12 manhour (T_{st}) times 250 NLG/hr (K_{st}), while the lower costs of planned preventive maintenance are estimated to be 9 manhour (T_{rev}) times 175 NLG/hr (K_{rev}).
Costs of consequences are caused by the unexpected delay of ships (15/day and 300 NLG/hr) which are expected to arrive equally spread in time. So these costs (K_g) are: 0.5*12*15*300 = 27.000 NLG.

The transmission part is characterized by the corresponding values:
- Random failure period of 12 years (T_0)
- Constant failure rate of 0.005 per year (Z_0).
- Mean lifetime of 25 years (T_{gf}).
- Fixed cost of maintenance 50.000 NLG (K_v)
- Costs of corrective maintenance:
  18 hr (T_{st}) times 250 NLG/hr (K_{st}).
- Costs of preventive maintenance:
- 14 hr (T_{rev}) times 175 NLG/hr (K_{rev}).
- Costs of consequences (K_g): 0.5*18*15*300 = 40.500 NLG.

With the help of KMOSS the cost optimal use based maintenance strategies of the mechanisms of movement may be found.

The driving part:	Optimal time of revision is 14,2 year (T_r) with total level of costs 1817 NLG/yr (K_{tr}).
Transmission part:	Optimal time of revision is 22,6 year (T_r) with total level of costs 3436 NLG/yr (K_{tr}).

Step 5: Tuning of the main maintenance actions.
Combining the use-based strategies of these two mechanical components give the next intervals:
- Both parts at a 19 years cycle (total costs 5524 NLG/yr).
- Alternating intervals : the driving part every 12.5 year and the transmission part every 25 year (total costs 5312 NLG/yr).

So combined revision is only economic if the advantage is more than 59 NLG/yr (= 5312 – 1817 – 3436). Notice that because of relative low costs of consequences in relation to the cost of repair, the time of revision is rather indifferent.
Combining the (use-based) maintenance of civil-engineering and mechanical parts leads to an overall revision interval of 19 years.
With the restriction that so the total economic advantages should be more than 1137 NLG/year (= 5524 – 1817 – 3436 + 5734 – 4868).

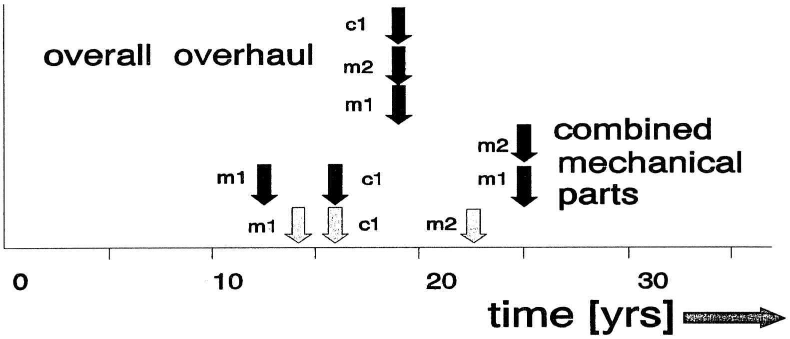

Fig. 9. Three maintenance strategies for the main components.

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