ENVIRONMENT-FRIENDLY MAINTENANCE OF PROTECTIVE PAINT SYSTEMS AT LOWEST COSTS[1]

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Abstract. The Netherlands Ministry of Transport, Public Works and Water Management (Rijkswaterstaat) is responsible for the construction, operation and maintenance of a large number of infrastructures. The inventory mainly consists of bridges, tunnels, storm-surge barriers, sluices and highway-signal systems. Rijkswaterstaat spends € 40 to € 50 Million per year on maintenance of coatings. The total amount of steel surface that has to be maintained is about 6 Million square metres. The maintenance costs are mainly determined by environmental costs. The trend of the last fifteen years is that the price per square metre is increasing, whereas the durability of coating is decreasing.

In this paper, we present the way Rijkswaterstaat deals with the maintenance of protective paint systems on steel structures. The maintenance strategy used in the Netherlands is based on functional requirements, which have been specified in technical regulations. The maintenance of paints on steel will be considered with emphasis on the use of the Lifetime-Extending Maintenance (LEM) model. The LEM model determines the cost-optimal combination of the interval of lifetime extension and the interval of preventive replacement. It has been applied to optimise the maintenance of the coatings on the steel gates of the Haringvliet storm-surge barrier. A Life-Cycle Analysis (LCA) was used to lower the

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environmental impact. Applying the LEM model in daily practice, results in sustainable infrastructures at lowest life-cycle costs.

Introduction

Reducing maintenance costs while keeping the infrastructure in function is one of the main concerns of the Netherlands Ministry of Transport, Public Works and Water Management (Rijkswaterstaat). The department is responsible for the main highway network, the main water network and the water quality. Maintenance costs were increasing, while the justification and prioritisation of maintenance measures were lacking. The costs for coating maintenance were rapidly increasing over the last 15 years, mainly due to more tight environmental legislations. To control costs, Rijkswaterstaat is developing and implementing a new maintenance management methodology. The aim of this paper is to place coating maintenance in the context of this methodology and to present the Lifetime-Extending Maintenance model (LEM model). The LEM model is used in a case study on maintaining the coating on the steel gates of the Haringvliet storm-surge barrier. Ultimately, we search for an optimum between the three dominant factors in coating maintenance: costs, durability and environmental protection.

Overall maintenance management methodology

In the Netherlands, maintenance of structures is planned on the level of structural elements. These elements are characterised by their specific technical and functional properties, and financial value. Technical documents, plans and procedures were introduced for optimising maintenance of civil structures.

Methodology

The maintenance methodology used in the Netherlands distinguishes three hierarchical system levels: networks (e.g. a highway network), structures (e.g. a bridge) and elements (e.g. a joint, a coating). Functional requirements have been defined for each type of element. At this level there are two possibilities. Either the structure fulfils all requirements or it does not. If the element fulfils the requirements only routine maintenance is required (e.g. cleaning the surface) and preventive maintenance can be applied to extend the lifetime of the element. If the structure does not comply with the requirements, corrective maintenance, or even replacement of the element will be necessary.

Maintenance strategies

For each specific element, a maintenance strategy is set up. In most situations, a maintenance strategy based on the inspection of a structure’s condition is most appropriate. This is known as condition-based maintenance. The next step is a prediction of the maintenance costs based on cost indicators and maintenance intervals for standardized measures.

An accurate estimate of the maintenance intervals and the cost of standardized measures is an essential, but difficult part of the methodology. Three phases of this process can be distinguished: the start with figures based on expert judgment, then the complete cost calculation for the standardized measures combined with actual data of maintenance intervals, and finally the use of deterioration models and data of physical parameters to predict the maintenance costs. The learning cycle of forecast, comparison with experience and evaluation resulting in a more accurate prediction has to be established. This paper will demonstrate how this learning cycle works in practice for coatings.

Maintenance strategy for coatings

For each group of similar elements (e.g. coated steel) the strategies are described in the so-called Reference Documents. These documents describe the functional requirements of coating systems on steel, the deterioration process, the maintenance strategy, the maintenance measures, the maintenance intervals, including standardized budget items and an inspection strategy. These items will be explained in more detail below.

Functional requirements of coatings on steel

The primary function of the coating system on steel is to protect the steel from degradation in terms of corrosion. The goal is to guarantee the function of the object where the coating system is applied upon, during the expected service life and at lowest life-cycle costs.

Dominant failure mechanism and deterioration process

The failure mechanism and the deterioration processes are related to the coating system and not to the steel. The failure mechanism of the coating system is a combined process of six predominant factors: blistering, corrosion, cracking, flaking, thinning (reduction of coating thickness) and adhesion of the coating. The deterioration process of the coating system is a combination of several processes such as the exhaustion of anti-corrosion pigments, decrease in diffusion resistance, decomposition of the binder, loss of elasticity, loss of adhesion, etc. The process of degradation will result in loss of the functionality of the coating system, so repair or replacement is needed. This process determines the lifetime in a specified environment.

Condition parameters and intervention levels

To measure the degradation, the six condition parameters as mentioned above were defined. For these parameters, intervention levels were defined on the basis of expert judgment.

For coating replacement, condition parameters are clustered: the surface to repair is expressed as a percentage of the total surface of the steel structure. The repair surface is the surface that has to be pre-treated and coated. This surface is of course larger than the actual corroded surface.

Maintenance strategy and measures

For defining a maintenance strategy, it is important that information about the durability of the coating is available and that maintenance costs can be optimised. For coating maintenance this is the case. The maintenance strategy is lifetime-extending maintenance. The condition of the coating can be determined by visual inspection and maintenance will be performed when the intervention level is exceeded.

For coating maintenance we define two measures: Lifetime-Extending Maintenance (LEM) and Coating Replacement (CR). LEM consists of cleaning by hand and spot repair of the coating system without large-scale environmental precautions. LEM is applied to damage-sensitive areas of the steel structure such as sharp edges, corners, welds, and other joints.
With CR, the object can be brought into a perfect condition again by thorough cleaning, grit blasting and airless spraying of the coating. This is done by spot repair as well as by totally removing and replacing the old coating system. If these operations are executed, serious environmental precautions are required.

Environmental precautions

A special environmental legislation exists in the Netherlands for protecting the surface water nearby steel structures. This legislation predominantly affects the costs of coating maintenance (LEM and CR). The precautions are divided into several protection classes. For the highest class, these precautions consist of a protective shielding, which completely seals off the maintenance activities from the environment. When using environment-unfriendly coating systems (e.g. coal tar epoxy coatings) the highest class of protection is prescribed. Because an environmental protective shielding is very expensive, the aim is to execute maintenance in the lowest protection class to save costs and not to harm the local environment.

Cost parameters.

In the Reference Documents cost parameters are developed for coating maintenance. The cost parameters include direct costs and indirect costs. The direct costs include the costs of pre-treatment and application. The indirect costs include the costs of construction, transportation and working area. Not included are costs for traffic precautions, engineering, personnel and VAT rate.
The indirect costs for LEM are much lower than for CR.

Maintenance and replacement intervals

In the Reference Documents, the maintenance and replacement intervals are listed for different coating systems combined with different environmental classes according to ISO 12944.
In order to inform the owner of the structure with more adequate knowledge, a study is executed "How LEM affects CR in practice". Therefore, the Lifetime-Extending Maintenance model (LEM model) was developed and now maintenance costs can be calculated over an unbounded horizon.

Lifetime-Extending Maintenance model

With the LEM model both the interval of lifetime extension and the interval of preventive replacement can be optimised. Through lifetime extension, the deterioration can be delayed and failure postponed such that the lifetime (of an element) is extended. Through replacement, the condition of an element can be restored to its original (perfect) condition. Lifetime-extending maintenance is defined as the maintenance of one element (e.g. a coating protecting steel) to extend the lifetime of another element (e.g. the steel). The LEM model has been applied for justification and optimisation of maintenance in the Netherlands (Klatter et al., 2002); detailed information regarding this decision model can be found in Van Noortwijk (1998) and Bakker et al. (1999).

The inputs of the LEM model are deterioration, lifetime-extension and cost parameters.

Deterioration parameters

A difficulty in modelling maintenance is the uncertainty in the process of deterioration and the time of failure. The uncertainty in the deterioration can be specified in terms of a stochastic process (in the LEM model this stochastic process is a gamma process, which is a stochastic process with independent and gamma-distributed increments). In structural engineering, condition failure is defined as the event in which -due to deterioration- the condition (resistance) drops below the failure level (design load). It is assumed that the expected deterioration at time t can be described using a power law; that is, the expected deterioration at time t can be written as at^b where $a > 0$ and $b > 0$. The uncertainty in the deterioration process is represented by the coefficient of variation (defined as the standard deviation divided by the mean value) of the deterioration at the time at which the expected deterioration equals the failure level.

Lifetime-extension parameters

In the LEM model, a deterioration process with lifetime extension can usually be subdivided into two parts: (i) an initiation period and (ii) a propagation period. During the initiation period, the lifetime-extending measure is fully effective and the structure does not deteriorate at all. During the propagation period, the lifetime-extending measure loses its effectiveness and the deterioration starts. The “net propagation curve” (Figures 1 and 4) is defined as the curve describing the condition without lifetime extension as a function of time, starting at the beginning of the propagation period. LEM can be superposed on this net propagation curve, which results in the overall condition with lifetime extension. Possible LEM measures are:

- Starting a new initiation period (Figure 1);
- Improving the condition of the element (Figure 4);
- Changing the rate of deterioration:
  - *Repeating:* After each lifetime extension the rate of deterioration is the same and equals the rate of deterioration of the net propagation curve at time zero; in other words, after each lifetime extension the propagation curve repeats (see Figure 1);
  - *Non-repeating:* After a lifetime extension the propagation curve is the same as the net propagation curve at the corresponding condition (this is illustrated in the Haringvliet case study; see Figure 4).

To determine the moment of action, the condition should be described properly. In Figures 1 and 4, two examples of condition description are given. In Figure 1, the condition is described in mm being the surplus in average thickness of a steel plate (adapted from Bakker et al., 1999). The lifetime of the steel is extended by grit blasting (with 0.1 mm loss of steel thickness), as well as by placing the new coating. The expected condition without lifetime extension in Figure 1 represents the corrosion process given initiation at time zero. In Figure 4, the condition is described with the percentage of the steel surface not being corroded. The lifetime of the steel is extended by spot repair of corroded areas.

The deterioration process with lifetime extension has been approximated by a deterioration process without lifetime extension. The approximate expected deterioration is a least-squares power-law fit to the lower envelope function of the exact deterioration process with lifetime extension. The coefficient of variation of the deterioration at the time at which the expected deterioration equals the failure level, is unchanged. The lifetime-extension parameters describe the effect on the net propagation curve after carrying out LEM, as described above.

Cost parameters

The cost can be distinguished in four parameters:

1. Cost of investment (construction)
2. Cost of preventive replacement (replacing before failure)
3. Cost of corrective replacement (replacing after failure)
4. Cost of lifetime-extending maintenance.

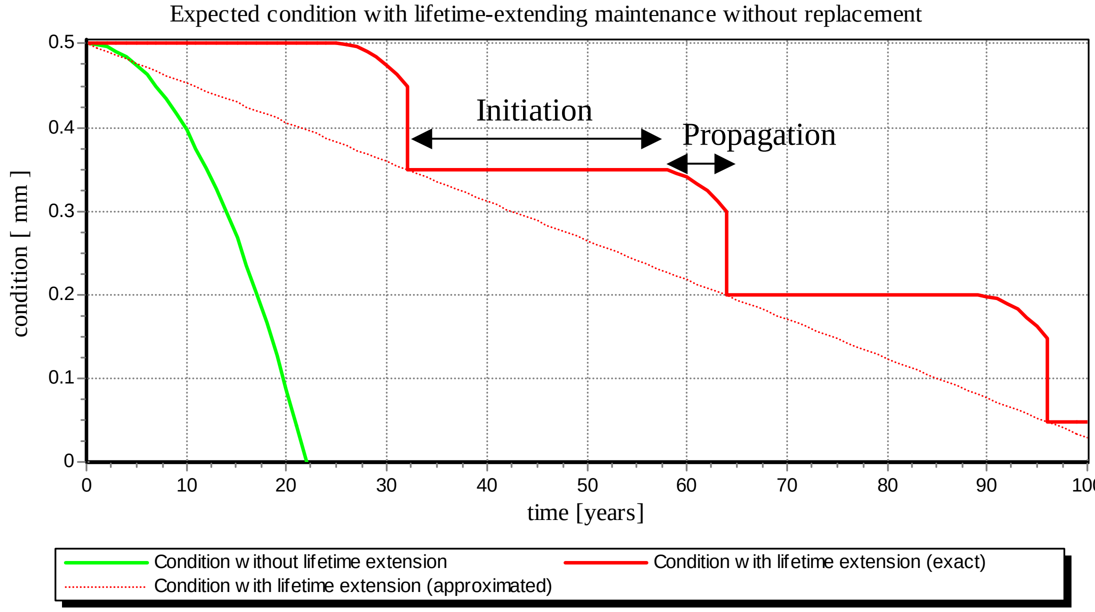

Figure 1. Expected condition of steel under corrosion with 'repeating' lifetime extension in terms of grit blasting.

For each combination of the interval of lifetime extension and the interval of preventive replacement, the LEM model calculates the expected discounted costs over an unbounded horizon (Van Noortwijk, 1998). The expected costs are determined by summing up the present values of the costs over an unbounded horizon. The future costs are discounted on the basis of a long-term discount rate (usually defined as the nominal rate of interest minus the rate of inflation). The expected discounted costs over an unbounded horizon are also denoted by the Net Present Value (NPV). The LEM model enables optimal lifetime-extension and replacement decisions to be determined for which the expected discounted costs are minimal. By using this decision model, we can find an optimum balance between the cost of preventive maintenance (lifetime extension and preventive replacement) and the cost of corrective maintenance (corrective replacement and failure).

The output of the LEM model consists of the optimal preventive lifetime-extension interval and the optimal replacement interval, as well as the expected time to failure and the minimum NPV. Notice that if corrective replacement is optimal, the optimal preventive replacement interval is (theoretically) unlimited.

Applications

In the past, the LEM model has been applied to optimise the maintenance of a coating protecting steel subject to corrosion (Bakker et al., 1999) and the repair of a concrete bridge subject to chloride-induced corrosion of the steel reinforcement (Van Beek et al., 2003).

In the next section, the decision model is applied to optimise coating maintenance of the Haringvliet storm-surge barrier.

Maintenance of the coating of the Haringvliet storm-surge barrier

The LEM model has been applied to optimise maintenance of the coating on the steel gates of the Haringvliet storm-surge barrier (see Figure 2). In 1970 the Haringvliet was closed off from the sea by the Haringvliet barrier. The Haringvliet forms a part of the Rhine-Meuse estuary in the Netherlands. It is a large river branch of about 20 km length and 2-3 km width. The Haringvliet barrier forms a 2 km long dam containing 17 gates. The Haringvliet barrier protects the inland from the sea and regulates the water discharge from the Rhine and the Meuse into the sea.

Figure 2. Haringvliet barrier in the Netherlands (Photography: Limit Fotografie Goes).

During the service life of the barrier, maintenance is needed for the gates to remain fit for use. During the construction of the barrier, a maintenance plan was made. But until now -after almost 35 years- not all planned maintenance actions were carried out. The main reason is that the maintenance costs were much higher than expected. Yet, in the period from 1988 to 1997, all coatings were replaced completely. On the average, the coatings of two gates were replaced every year.

By using the LEM model, we can obtain a cost-optimal strategy for maintaining the coating of the steel gates. The aim is to determine a cost-optimal combination of the interval of lifetime extension and the interval of preventive replacement. For this purpose, the input parameters of the LEM model (deterioration, lifetime extension and costs) are specified for the steel coating. The assessment of the deterioration parameters is based on inspection results and expert judgment.

Inspection results

In 2002, the coating of about half of the Haringvliet gates were inspected. A representative selection of gates was made, considering the year in which the coating was applied. A distinction was made in gates at the riverside and at the seaside. In this paper, we will focus on the seaside gates. Due to the salt-water environment, the corrosion process is more severe at the seaside gates than at the riverside gates. The inspection results of the seaside gates are given in Table 1. In this table, both the corroded area and the area to be repaired are given (on the average, the area to be repaired is 6.75 times as large as the corroded area). The results are based on the restriction that only 10% of the total area of a gate is inspected. The gate where the coating is applied first has the largest corroded area and visa versa.

Gate	**Placement complete coating [year]**	**Total gate area [m^2]**	**Total inspected area [m^2]**	**Corroded area**		**Area to be repaired**	
				[m^2]	**[%]**	**[m^2]**	**[%]**
1	1988	5400	545	11.46	2.10	45.46	8.30
4	1990	5400	545	4.08	0.75	23.21	4.20
7	1992	5400	545	4.59	0.84	23.80	4.30
15	1994	5400	545	2.23	0.41	14.95	2.70
13	1996	5400	545	1.47	0.27	20.30	3.70

Table 1. Overview of the inspection results of the seaside gates.

Deterioration parameters

To assess the parameters of the deterioration process and the time of failure, the five inspection results were assumed to be of the same steel gate; there is no spatial variation. This means that we can use the inspection results as if they were from one gate.

To assess the deterioration, we identify the following six condition parameters: the amount of blistering, corrosion, cracking and flaking, the coating thickness, and the adhesion of the coating. For these condition parameters, the intervention levels are determined based on expert judgement. A distinction is made between LEM and CR. The three condition parameters related to LEM are: corrosion, cracking and flaking (standard ISO 4628). All six parameters are related to CR. The intervention level for CR is defined as follows. CR is performed if the deteriorated area is larger than 20%. In the previous paragraph, it is already mentioned that the area to be repaired is 6.75 times as large as the corroded area. Based on this information, we define the failure level -in accordance with the Reference Documents- as follows: if the corroded area is larger than 3% of the total area of the gate, then the coating on the gate has failed and CR is needed. If the corroded area is less than or equal to 3% of the total area of the gate, then LEM is needed.

Deterioration parameter	**Value**
Initial condition (non-corroded area)	100 %
Failure condition (failure level)	97 %
Initial condition minus failure condition	3 %
Lifetime at failure	19 year
Parameter *a*	0.0048
Parameter *b*	2.19

Table 2. Deterioration parameters of seaside gates.

The expected deterioration in time is assumed to be described as a power law. Based on the inspection results, the parameters *a* and *b* are estimated using the least-squares method (see Table 2). The expected deterioration is shown in Figure 3. The figure shows that after about 19 years, the condition drops below the failure level being a corroded area of 3% and a non-corroded area of 97%. The uncertainty in the deterioration process (a gamma process) is shown in Figure 5 and it is estimated using expert judgement. The corresponding coefficient of variation of the deterioration at the time at which the expected deterioration equals the failure level is 0.3.

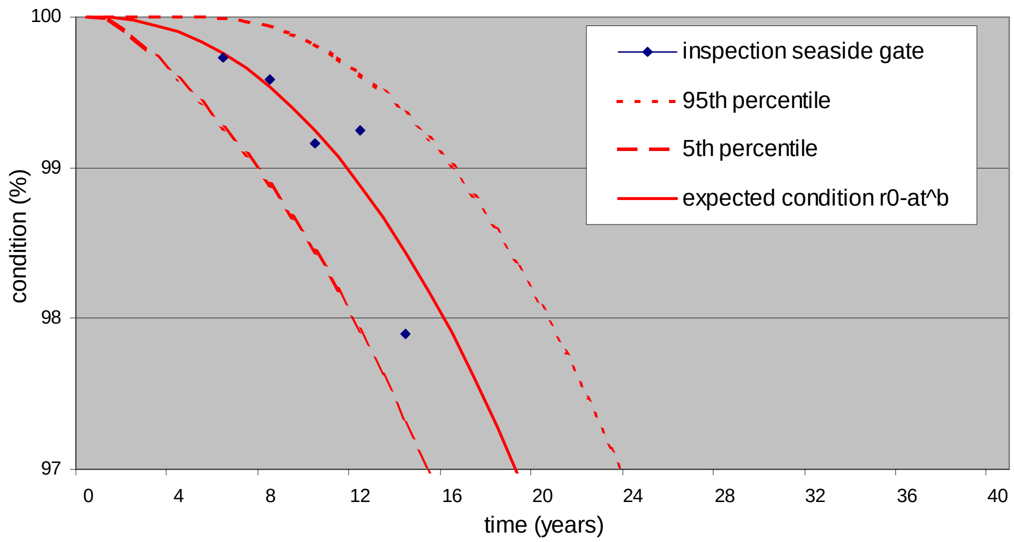

Figure 3. Expected deterioration including inspection results and uncertainty.

Lifetime-extension parameters

For the deterioration process of the steel coating with lifetime extension, we assume that the initiation period is zero and the deterioration sets in immediately after a lifetime-extending measure (see Figure 4). Using expert judgement, we assume that the condition improves with 0.8% and that the deterioration process with lifetime extension is non-repeating. On the basis of experiences with the maintenance of the Haringvliet barrier, we expect the lifetime of the coating to be extended with ten years as a result of LEM.

Cost parameter	Value
Cost of lifetime-extending maintenance	20 k€ per gate
Cost of preventive/corrective replacement of complete coating	1091 k€ per gate
Annual discount rate	4%

Table 3. Cost parameters of maintaining the coating.

Cost parameters

To determine the cost-optimal maintenance strategy for the coating of the Haringvliet gates, we need the cost of lifetime extension and the cost of replacement of the whole coating of the gate (see Table 3). The maintenance cost is adapted from the Reference Documents. Costs of preventive and corrective replacement are identical, because they are both largely determined by expensive measures for environmental precautions.

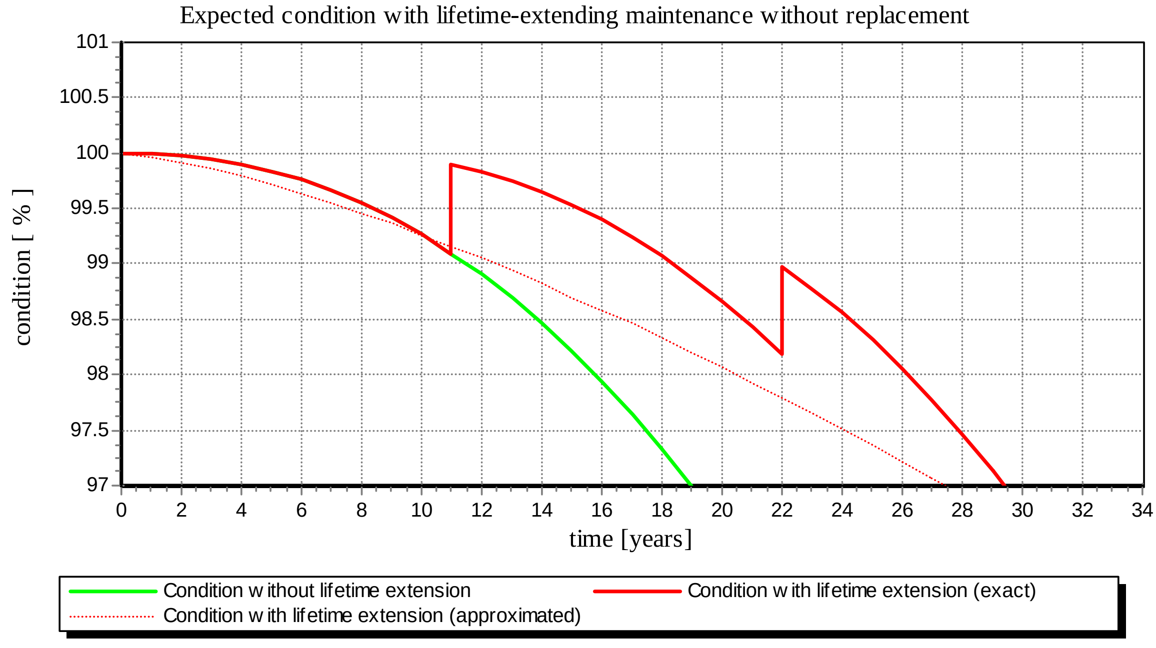

Figure 4. Expected condition of the coating with 'non-repeating' lifetime extension in terms of condition improvement.

Maintenance strategy based on cost optimisation

Based on the above-mentioned input parameters, the cost-optimal maintenance strategy for the coating on the gates of the Haringvliet barrier can be computed by the LEM model. The decision variables in the LEM model are the lifetime-extension interval and the preventive replacement interval. The output of the LEM model is given in Figure 4. The figure shows that the optimal interval for lifetime extension, with an improvement of the condition with 0.8%, is 11 years. The lifetime of the coating is extended from 19 to 29 years. Because corrective replacement is optimal, the optimal preventive replacement interval is (theoretically) unlimited. Summarising, the cost-optimal strategy is lifetime-extending maintenance by means of spot repair once in 11 years, where the complete coating is expected to be (correctively) replaced once in 29 years.

Maintenance strategy based on experience

Based on practical experience with past maintenance of the Haringvliet gates, the actual cost of maintenance appears to be much higher than the cost adapted from the Reference Documents. The cost of lifetime extension is almost 40 times as high (k€ 750 per gate) and the cost of replacement of the coating almost twice as high (k€ 2000 per gate). These differences are mainly due to the exceptional measures (such as waste disposal and protective shielding) that must be taken to protect the environment when maintaining the coating of the large gates of the Haringvliet barrier. In practice, larger areas need to be repaired than assumed in the Reference Documents. Furthermore, the necessary maintenance is more than just spot repair of the corroded areas; the corroded areas need to be grit blasted. Hence, more measures must be taken to protect the environment when maintaining the coating of gates. Besides, in the Reference Documents these costs are much less because they are connected with averaged-sized – smaller- steel doors. If the cost parameters are the higher experience-based costs, the LEM-model results change considerably. The optimal maintenance strategy is then CR, rather than LEM. The complete coating is expected to be (correctively) replaced once in 19 years. The resulting expected deterioration corresponds to the 'Condition without lifetime extension' in Figure 4.

Environmental impact of coating maintenance

Rijkswaterstaat has performed research on the environmental impact of coating maintenance by comparing two different coating systems: one was based on a coal tar epoxy system and one was based on a modern low VOC epoxy system. Also the actual amounts of emissions during maintenance have been investigated. Rijkswaterstaat has developed a brief LCA method to determine the environmental impact. The main conclusions are described below.

Coating maintenance affects the environment by two important factors. The first factor is the composition of the coating system, which affects the environment mainly in the application phase during maintenance. The second factor is the durability of the coating system. Important factors during maintenance are the application and the removal of the coating system. The most expensive contributors are: the energy consumption, the coating consumption, the emissions of VOC, and the use of blasting grit and the transportation and storage of the wasted blasting grit. The environmental impact also depends on the local environmental circumstances; for example, special flora and fauna in combination with the water quality.

A practical study has shown that power tool cleaning with exhausters can significantly reduce the amount of emissions during LEM. Reductions are estimated up to 50%. For a modern low VOC epoxy coating system, the amounts of emissions per square metre are 260 milligrams of inorganic compounds and 1625 milligrams of organic materials.

Rijkswaterstaat has developed a brief LCA method. The main environmental impacts are defined as: energy, smog, human and eco toxicity, and dangerous and non-dangerous waste. A stepwise plan for such a brief LCA is described in more detail in the *Rijkswaterstaat Methodology for Choosing Paint Systems* (Heutink, 2001, pages 29-32). A problem in practice is the lack of available data from coating manufacturers to make proper judgments on the environmental impacts.

The relation between environmental aspects and maintenance costs is becoming clearer. Dominant factors are the durability and environmental impact of the applied coating and the costs of environmental measures during maintenance. Therefore, it is necessary that more durable coatings will be developed in relation to their environmental impact. Methods to select these coating systems from the market are important (Heutink et al., 2002; Van der Schaaf, 1998).

Conclusions

We described the Rijkswaterstaat maintenance methodology and how it is used for coating maintenance. This methodology has proven to be useful in practice in order to control costs and to keep the steel structures functional.
We explained the background of the Lifetime Extending Maintenance model (LEM model) and how to use it in practice, illustrated by coating maintenance of the Haringvliet storm-surge barrier. Costs for environmental protection are dominant in finding the optimal strategy. In practice, these costs can be much higher than expected (in the Reference Documents) due to object-specific circumstances. The LEM model is a useful tool for determining the optimal combination of the interval of lifetime extension and the interval of coating replacement. To increase the reliability of the model’s outcome, it is necessary to have more accurate input data such as inspection results and maintenance costs.

Durability is the most important factor in an LCA. More accurate data is needed about the coating composition and its durability. To select the most durable coating systems for infrastructures, Rijkswaterstaat has developed a new method. Tests resulted in 13 different coating systems, divided over 3 different object types (e.g. sluices/splash zone, over and below bridges). Data about the coating composition is needed to determine the environmental impact.

Rijkswaterstaat has developed a method by which coating maintenance can be justified and prioritised better, while saving costs, protecting the environment and maintaining functionality. It is necessary that environmental legislations provide some flexibility in order to protect the environment over the total service life of the steel structure. The role of paint manufacturers is significant in finding more durable protective coating systems. Rijkswaterstaat has made a big step forward towards a sustainable steel infrastructure at lowest life-cycle costs, although more research is needed.

The Lifetime-Extending Maintenance model is freeware and can be obtained by contacting Mr. Jaap Bakker of the Rijkswaterstaat via E-mail at j.d.bakker@bwd.rws.minvenw.nl or via Internet at http://www.bouwdienst.nl/lem.

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References

1. J.D. Bakker, H.J. van der Graaf, and J.M. van Noortwijk. Model of Lifetime-Extending Maintenance. In M.C. Forde, editor, *Proceedings of the 8th International Conference on Structural Faults and Repair, London, United Kingdom, 1999*. Edinburgh: Engineering Technics Press, 1999.
2. A. Heutink, W. Bonestroo, J. van Montfort. *Coating systems for infra structural works,* 26th Fatipec congress Macromolecular Symposia, Volume 187, pages 23-34, Dresden, Germany, 2002.
3. A. Heutink, User guide, *Rijkswaterstaat Methodology for choosing paint systems*, Version 2.0, Ministry of Transport, Public Works and Water Management, Civil Engineering Division, Utrecht, Netherlands, 2001.
4. H.E. Klatter, J.M. van Noortwijk, and N. Vrisou van Eck. Bridge management in the Netherlands; Prioritisation based on network performance. In J.R. Casas, D.M. Frangopol, and A.S. Nowak, editors, *First International Conference on Bridge Maintenance, Safety and Management (IABMAS), Barcelona, Spain, 14-17 July 2002*. Barcelona: International Center for Numerical Methods in Engineering (CIMNE), 2002.
5. A. van Beek, G.C.M. Gaal, J.M. van Noortwijk, and J.D. Bakker. Validation model for service life prediction of concrete structures. In D.J. Naus, editor, *2nd International RILEM Workshop on Life Prediction and Aging Management of Concrete Structures, 5-6 May 2003, Paris, France*, pages 257-267. Bagneux: International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM), 2003.
6. T. van der Schaaf, *New developements and trends in the protective coatings industries in the Nethelands, Orlando, Florida, 15-19 November 1998*, SSPC Seminars, Increasing the value of Coatings, pages 147-151, 1998.
7. J.M. van Noortwijk. Optimal replacement decisions for structures under stochastic deterioration. In Andrzej S. Nowak, editor, *Proceedings of the Eighth IFIP WG 7.5 Working Conference on Reliability and Optimization of Structural Systems, Kraków, Poland*, 1998, pages 273-280. Ann Arbor: University of Michigan, 1998.