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Durability Research as an Investment Strategy

Recherches sur la durabilité pour une stratégie d'investissement

Dauerhaftigkeitsforschung als eine Investitionsstrategie

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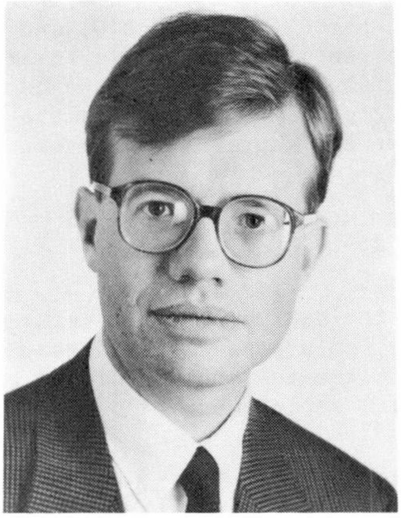

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SUMMARY

If the optimality of a structure as well as of its programme of maintenance and renewal is measured by total present value, any addition to our knowledge of the durability of materials and components should be measured by its contribution to this value. It follows that the economic consequences of research projects on durability can be studied with a strategic perspective.

RÉSUMÉ

Si l'optimum économique de la conception d'un ouvrage ainsi que de son programme d'entretien et de renouvellement est mesuré à sa valeur totale actualisée, tout progrès de nos connaissances concernant la durabilité des matériaux et composants doit être évalué en fonction de sa contribution à cette valeur. Par conséquent, les effets économiques de projets de recherche sur la durabilité sont étudiés dans cette perspective de stratégie.

ZUSAMMENFASSUNG

Wenn die Qualität eines Bauwerks sowohl am Bauwerk selbst als auch am zugehörigen Programm für Instandhaltung und Erneuerung als Gegenwartswert beurteilt wird, so ist jede Vermehrung unserer Kenntnisse bezüglich der Dauerhaftigkeit von Baustoffen und Komponenten nach ihrem Beitrag zu diesem Wert zu beurteilen. Auf dieser Grundlage werden die wirtschaftlichen Folgen von Forschungsprojekten über Dauerhaftigkeit mit einer strategischen Perspektive untersucht.

1. INTRODUCTION

1.1 Profit maximization

The choice of materials and components as well as maintenance and replacement policies over time can be formulated as a profit-maximization problem for the owner of a structure or group of similar structures. Let $Q(t)$ be the quality of the structure at time t and assume that the stream of revenues R from the use of the structure is a function of quality, $R = R[Q(t)]$. The stream of costs $C(t)$ is initiated by construction costs $C(0)$ and after $t = 0$ caused by maintenance and replacement expenditure. The time horizon for the maximization is $t = T$, which may or may not be the date of total demolition of the structure. Finally, the rate of discount which expresses the time preferences of the owner is taken to be ϱ, and we can express the present discounted value as follows:

$$\int_0^T \{R[Q(t)] - C(t)\} e^{-\varrho t} dt$$

Over the chosen time period, the maximum present value is to be achieved. By application of control theory, solutions can be found, giving not only the optimal maintenance paths but also the optimal timing of discontinuous increases in $Q(t)$, i.e. partial replacement [1].

1.2 Revenues

For most structures, the stream of revenues is not immediately known. Even when the structure or the services of the structure appear on the rental market or is subject to user fees, the relation between R and $Q(t)$ may be difficult to ascertain. This is especially true of the influence on revenues of small changes in functional quality, although the development of a range of quantitative indicators for the functional condition of road surfaces shows what is feasible for large systems of infrastructure under a unified management [2].

However, many of the structures lacking an easily identifiable stream of revenues are managed on the principle of approximately constant quality over time. The optimization is then equivalent to a minimum life-cycle cost approach [3].

1.3 Costs

Costs of maintenance and replacement may appear easier to predict than the effect of quality changes on revenues. An exception is when there is a possibility of cumulative damages occurring on failure of a structural part, as with reinforced concrete [4]. Risk analysis based on a mapping of failure mechanisms, their wider consequences as well as maintenance and replacement options, should then be performed, provided that the analysis in itself gives a positive net contribution to the expected present value.

1.4 Data and level of application

In current practice, direct optimization is usually ruled out because of lack of data, discontinuities and complex patterns of interaction. Depending on the type of structure, obstacles to data access arise from fragmented and competitive ownership or high costs of collecting data for a unique structure subject to a unique environment. To some extent, advances in information technology will improve the availability of data. Regarding discontinuities and complexities, the theory as it is can only be applied at a suitable level of aggregation: applied to a system of several structures rather than the individual one, so that behaviour over time and resource flows into maintenance can be approximated by continuous functions.

2. THE CONCEPT OF DURABILITY

2.1 Durability and service life

The related concepts of durability and service life are properly of interest only for the special case of materials and components that either perform their function or fail to do so. However, as concepts they provide a convenient focus for studies into the long-term behaviour of materials and components, not least for the large group of structures where there is a technology for recurrent maintenance as well as partial replacement, prolonging their lives and postponing total replacement. In practice, we encounter a long scale from partial replacement to total renewal.

Viewed under the appropriate magnification, any maintenance activity including cleaning or repainting falls into one or several of the categories of removal, replacement or addition of materials (or components). By disaggregating, a level can always be found where service life is a meaningful concept. Unfortunately, there are few cases where this level allows direct optimization. Nevertheless, research into durability of materials and structures is important because it focuses on $Q(t)$, or in other words, performance over time, in the form of degradation studies.

2.2 Degradation

Degradation of materials and components under the influence of various degradation factors [5] is the main object of durability studies. A variety of methods is available to the researcher, field studies, accelerated aging and the parallel development of theory, as in the case of concrete structures [6]. Degradation in an existing structure gives rise to maintenance and replacement needs.

3. MAINTENANCE AND INSPECTION

3.1 The quality path over time

The choice of maintenance policies is simplified in the constant quality case, although the determination of an optimal period of renewal will depend on the maintenance cost function. We should avoid looking at maintenance as an operation which in principle just restores the $Q(0)$ of the structure; in many cases, there is a technologically inseparable combination of activities intended to raise the load-bearing capacity or other qualities above the initial level. Conversely, it may be profitable to reduce the original quality level and remain at a lower level. Thus, from the economic point of view, the $Q(t) = Q(0)$ case is fortuituous or, if imposed as a restriction on the management of the structure, sometimes more due to difficulties in information handling than to functional analysis of the use of the structure.

Formulating the optimal maintenance path problem with the help of the theory of optimal control usually implies that the present value maximization is supplemented with a quality change restriction, where maintenance enters as a control variable:

$$\dot{Q}(t) = m(t) - \delta(t)Q(t)$$

where $m(t)$ is a measure of maintenance resources consumed at time t and $\delta(t)$ is the degradation or depreciation function. If $m(t) = 0$ and $\delta(t)$ = constant, the quality of the structure decays exponentially, as in Fig. 1. The two degradation paths based on δ_1 and δ_2 show the possible effect of durability research: either an improvement in the material so as to attain the δ_1 level or a narrowing of the uncertain area between δ_1 and δ_2, reducing the risk in choices during the design stage. In Fig. 2, the effect of durability studies on materials or components with a pattern of sudden failure is shown: either a prolongation of service life from t_2 to t_1 or a more narrow interval of life being predicted.

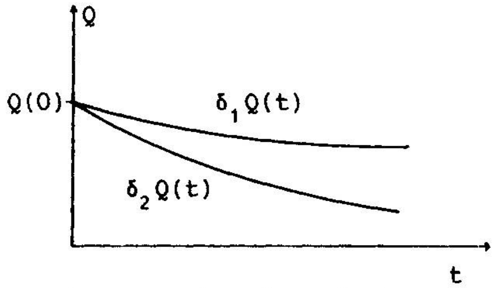

Fig.1 Successive degradation

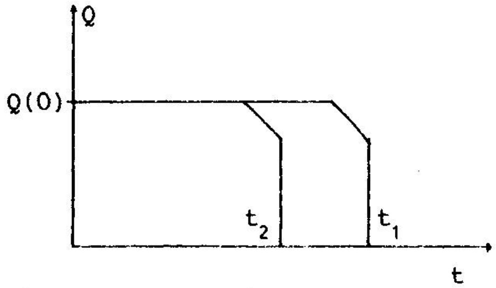

Fig. 2 Sudden failure

3.2 Preventing damages

Preventive maintenance may raise the present value if there is significant irreversibility in processes which start when quality declines below a certain level. Structural collapse is a typical example, roof leakage a less dramatic one. Optimal strategies for preventive maintenance can be condition-based, including routine inspection, or time-based (periodical), which should be the choice when the cost of inspection exceeds the expected increase in total present value associated with the structure.

The development of durability studies increases our ability to recognize and anticipate irreversible quality changes in a structure. Such knowledge can be translated into alternative patterns of inspection or even as the continuous monitoring of decay through the information network of an `intelligent' building. Inspection, the choice of intervals, the resources devoted to it and consequential savings, should be seen as a part of the maintenance strategy and as a part of a joint optimization problem for the assignment of scarce resources [7].

4. EVALUATING DURABILITY RESEARCH

4.1 The economic value of research findings

The findings of durability research can be used in three contexts:

(a) in the materials industry, when developing new materials or combinations of materials,

(b) at the design stage, leading to better choices of materials and components;

(c) after completion of the structure, when choosing or modifying strategies of inspection, maintenance and replacement (partial or total).

For a given type of research projects, the relevant set of structures with reasonably similar technology and similar environmental conditions must be identified first, both existing structures and projects in the foreseeable future. Secondly, the situations of economically important choices in the three contexts (a - c) should be analysed. The analysis comprises an assessment of the range of substitute materials, both at present and over the lifetime of the structure, alternative methods of maintenance and the risks involved in deferred maintenance and replacement, at the present state of knowledge and as expected from the project in question. After that, present value analysis should be considered. As an example, the design choice between two paints A and B with different degradation properties, following as most surface materials do the pattern of Fig. 1, can be based on the ensuing maintenance costs [8]. The calculation is more complicated when assessing the value of risk reduction (in terms of Fig. 1, that the true degradation pattern is δ_1 and not δ_2, e.g.), and in the situation of Fig. 2 with sudden failure, the emphasis of the analysis is shifted towards a probabilistic approach, identifying risks and their relations. Finally, the potential for spin-off effects owing to new, more fundamental insights into decay mechanisms with a wider application should be assessed, although this is mostly a matter of intuitive judgment.

4.2 Recipients of benefits

Like most forms of research with a fragmented pattern of beneficiaries, it is difficult to finance activities by user fees according to benefits. Where there are single users of the information, such as materials producers with local monopolies in a uniform environment, or the structures - like many bridges - form part of a technical or legal monopoly, something approaching an efficient allocation of research resources should appear spontaneously. However, if materials and structures are sold in markets, where durability information is costly to transfer from seller to buyer, there will be insufficient incentives to improve the long-term performance through research. A textbook solution, when inspection and quality control costs are high in market transactions and there is a considerable risk of latent defects, is vertical integration through joint ownership of the stages of production. Since this is seldom the case for buildings and the physical infrastructure, cooperation and government support is needed to reach an efficient level of durability research.

The case of the monopoly producer of a material holds another complication. If the extended life of products reduces the total materials consumption per annum, and there are economies of scale in production, some of the returns to scale will be lost when sales decline [9]. On the other hand, the superior durability may lead to a wider market for the product, which compensates for the immediate loss of volume.

4.3 Quality of research

Especially where component failure may lead to severe damages, questionable validity and reliability of research findings introduces an important stochastic component. Also, it is often so that durability findings are loosely applied to a slightly different material subject to slightly different environmental action. Care should be taken that research methods and presentation of findings minimize additional risks in application. Expert evaluations of research projects is one of several ways to monitor the level of quality in durability studies [10].

5. AN INVESTMENT STRATEGY

Returning to the initial present value maximization, we can look at durability studies in the same perspective. The body of knowledge in the field of durability is treated analoguously with the structure, and the successive maintenance inputs have their parallel in additional research findings. Due to new discoveries and the general development of technology, parts of the existing knowledge are rendered useless, similar to the successive deterioration of Fig. 1. The revenues from durability research have to be derived from the savings made in materials production and in the management of erected structures.

In practice, the total optimization implied by this approach has to be replaced with a strategy of suboptimization: a set of priorities for investment in durability research should be established working backwards, primarily identifying alternative methods of maintenance and replacement, analysing how great the economic losses can be when durability characteristics of materials and components are known imperfectly.

6. CONCLUSION

Within the framework of present value analysis, it is necessary to consider both the long-term revenues and the costs associated with structures. A flexible view of maintenance and programs of partial replacement can then be applied and the value of durability research assessed in this context. For the specific case of sudden failures with major irreversible consequences, risk analysis should be used according to priorities based on an identified potential to contribute to overall present value. The lack of incentives for research is traced partly to the costs of knowledge transfer between sellers and buyers when markets for materials and structures exist. A tendency to underinvest in durability studies should be met by research cooperation and strong government funding.

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